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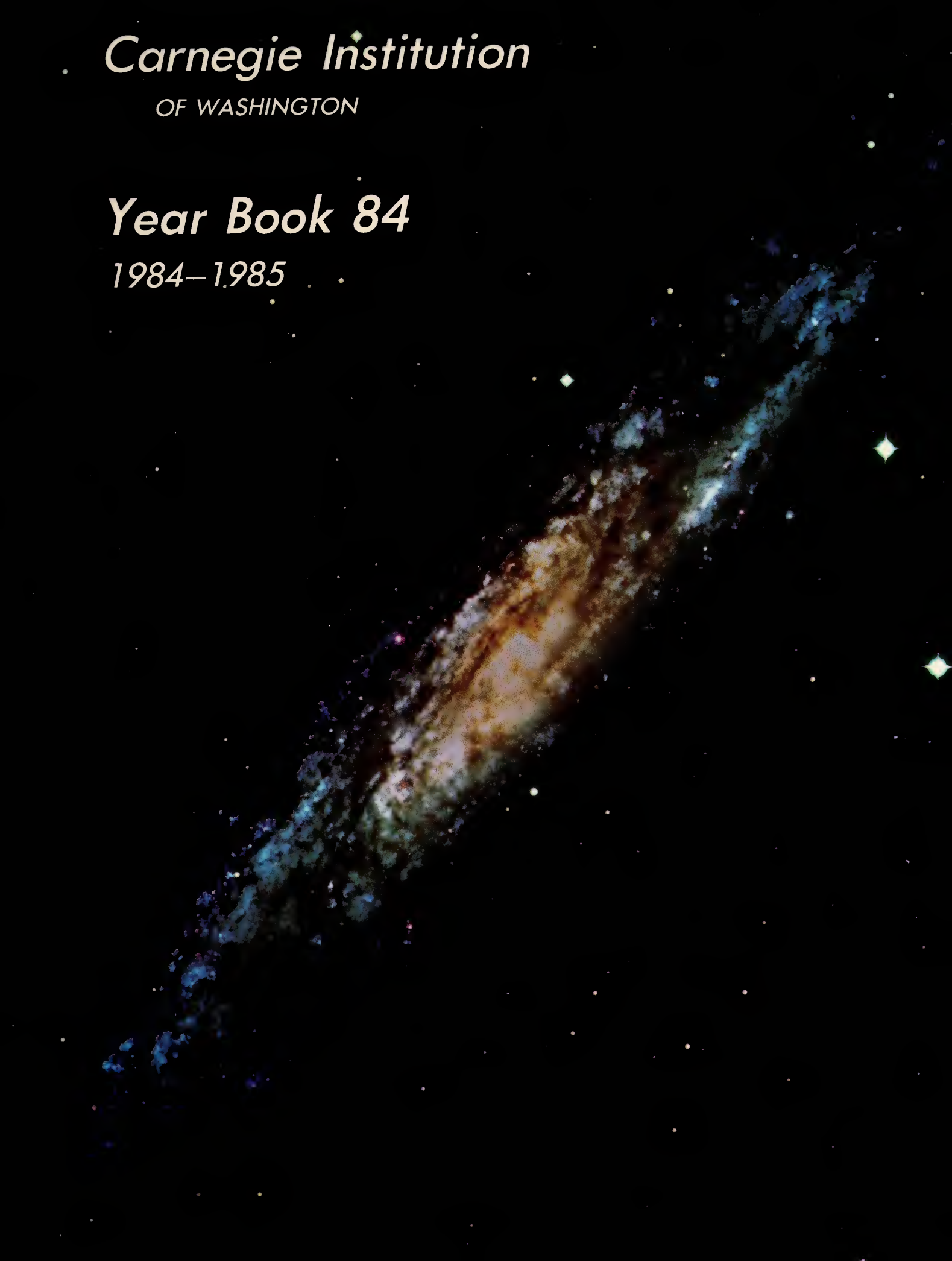

Cover: The Southern Hemisphere spiral galaxy NGC 253, imaged at the Institution's Irénée du Pont telescope at Las Campanas, Chile. The outer spiral regions, their appearance dominated by young stars rich in the heavier elements, are distinctly blue in color.

The color image was obtained by taking three black-and-white exposures through filters using photographic emulsions sensitive to different colors. These are combined in the darkroom in the reverse way through similar filters. The technique can be used to facilitate surveys for highly colored objects. The experiments and photographic work for this image were done several years ago by staff photographer John Bedke at Las Campanas and in the Observatories' photographic laboratory at Pasadena.

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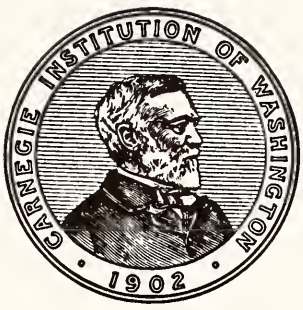

Year Book 84

THE PRESIDENT'S REPORT

1984–1985

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President's Commentary

Portions of two lampbrush chromosomes isolated from the nucleus of a newt oocyte (*Notophthalmus*) by Joseph Gall of the Department of Embryology. The loops extending laterally from the main axis are regions of active RNA transcription. The products of lampbrush chromosomes are of interest to Gall because they control events during oocyte growth and early stages of embryo development.
(See p. 27)

> Resolved that, because of the desirability of locating the Institution's programs in the Geophysical Laboratory and the Department of Terrestrial Magnetism onto a common site, the Institution proceed with plans for new or remodeled buildings for the departments at a single site. . . .
>
> Resolved that the Institution take the steps necessary to ensure its participation in a large new telescope, intending to commit by 1989 not less than $10 million toward the construction of a large telescope (8-meter) at Las Campanas, provided that engineering studies and site surveys, to be undertaken during 1985–1989, demonstrate its feasibility, and provided that agreements can be completed with the University of Arizona and, if appropriate, an additional partner.
>
> *Resolutions of the Board of Trustees*
> Carnegie Institution of Washington
> May 3, 1985

The major resolutions voted by the Institution's trustees in May were exhilarating in their implications for our future. Together, the resolutions reflect the trustees' determination that Carnegie Institution must stay at the forefront of discovery in the physical sciences. The decision to move toward a major, new telescope at Las Campanas signals that the Institution's astronomers will have the opportunity to remain leaders in investigating distant, extremely faint objects—a realm that seems to encompass many of tomorrow's most exciting questions. Meanwhile, the consolidation of the Geophysical Laboratory and Department of Terrestrial Magnetism brings together our leading investigators of several subdisciplines in the earth and planetary sciences, looking toward a new dimension of leadership in that increasingly exciting field.

In the months since May, we have been working to reach agreements that will determine the new workplace of our earth scientists and the partnership arrangements for building and operating the new telescope. Our discussions with representatives of major universities and research centers have been promising,

to say the least. The reaction of our alumni and peers to the courses we have chosen has been encouraging, and there is no shortage of prospective partners eager to share the future with us—a testimony to the reputation built by our earth scientists and astronomers in past decades. I can only hint at the details that are emerging, but my confidence in our basic direction is stronger than ever.

Our Future Leadership in Astronomy. Although the resolutions of the trustees were assuredly bold ones, it is also clear that the decisions are in harmony with the past history of the Institution—that they are as much evolutionary as revolutionary. Carnegie Institution's long leadership in observational astronomy, for example, has rested on its willingness to invest in the design, construction, and continuing improvement of major telescopes. A future 8-meter reflector at Las Campanas follows the tradition of the historic instruments on Mount Wilson and the central role of the Institution's astronomers in the development of the 5-meter telescope at Palomar.

The decision to proceed with a new telescope at Las Campanas is strongly related to the growing importance of observation in space. We are already witnessing a flow of major discoveries from the early spaceborne instruments, and the Hubble Space Telescope—scheduled for orbiting next fall—should become "the new Mount Wilson." We believe that the key to leadership in the future era of spaceborne observation will be access to major ground telescopes—to conceive and develop forefront observing programs that will use precious space telescope time to its fullest advantage. When completed, the great reflector at Las Campanas will allow our astronomers to compete effectively for observing time in space, and will give them the resources to explore extensively the clues likely to emerge from space. Moreover, our leading facilities in the Southern Hemisphere should give our scientists excellent opportunity to obtain access to the major telescopes of the North through exchanges of telescope time.

A related development was the cessation of observations at our historic 100-inch Hooker telescope, in late June 1985. This step was in accordance with our earlier decision to seek other operators for our facilities on Mount Wilson. The 100-inch continues to receive preventative maintenance and is exercised periodically to keep it in operating condition. For the time being, the stellar-activity observing program at the 60-inch telescope

and the regular observations at the Mount Wilson solar telescopes remain active, with contract support from outside sources. We continue to seek outside proposals for the continued operation of the Mount Wilson facilities, from any organization that can provide sound scientific and fiscal management. We believe that the resources conserved by curtailing our expenditures at Mount Wilson will be better employed to acquire advanced instrumentation, to upgrade our computers, and to work toward the future 8-meter instrument at Las Campanas.

Our Future Leadership in the Earth and Planetary Sciences. The forthcoming marriage of the Geophysical Laboratory and the Department of Terrestrial Magnetism (DTM) likewise appears a largely evolutionary response to today's opportunities. Collaboration between scientists of the two departments will not be new. Currently, there is sharing of computer facilities, frequent interaction in seminars, and occasional collaboration in research. Recently, knowledge developed at the Geophysical Laboratory was used to establish at DTM an ^{18}O measurement program, and the techniques for measuring ^{10}Be developed by Louis Brown of DTM and colleagues were used for collaborative investigations with Thomas Hoering of the Geophysical Laboratory on the origin of petroleum. Geochemists at both centers employ isotope analyses to study regions beneath the Earth's surface. The most notable example of past cooperation was the interdepartmental effort in developing techniques for geochronology and isotope geochemistry, begun around 1950 and lasting more than two decades. Interestingly, seismology—a major focus of effort at DTM today—was linked to the Geophysical Laboratory in the 1920s and 1930s through the work of director Arthur Day, who led a pioneering Carnegie-Caltech-U.S. government venture in seismology, primarily in California.

The Geophysical Laboratory brings to the forthcoming consolidation a philosophy of investigating fundamental principles, a remarkable record of success in conceiving and developing equipment and techniques for forefront experiments, and an insistence on rigor in obtaining and interpreting quantitative data. The Laboratory's director, Hatten Yoder, recently described the Laboratory's historic role:

> The Geophysical Laboratory has endured as a leader in earth science research because it has focused on well-chosen problems bearing on *major principles* that control geological phenomena. The experimental demonstration and verification of those princi-

ples have led to a framework for others to use in the resolution of current earth science problems.

The tradition at DTM has been wider ranging. The Department's initial focus on the Earth's magnetism has been stretched to include whatever ventures seem to the staff interesting and worthwhile, all generally focused toward an overall goal of understanding the Earth and Universe. The result has been a flowering of discovery and a vindication of the Institution's historic willingness to change—a tradition most clearly seen at DTM.

Today, knowledge in the subdisciplines of the earth and planetary sciences is pyramiding with incredible rapidity, and as the pyramids of knowledge grow taller they also grow wider. There is scarcely a significant question that does not demand synthesis across subdisciplinary boundaries. Seismologists, geochemists, computer-oriented theoreticians, and laboratory experimentalists ask many of the same questions. By bringing the investigators of DTM and the Geophysical Laboratory into daily interaction, and by merging the strengths of the two centers, the Institution's opportunities for future leadership in discovery must multiply.

A Time for Introspection. Amid our recent planning for the future, our attention returned periodically to our historical roots—a byproduct of the several recent observances commemorating the 150th anniversary of the birth of Andrew Carnegie. It proved useful on these occasions to reexamine Mr. Carnegie's purposes in founding the Institution, and to review the Institution's subsequent evolution over eight decades. Our Institution's character remains a reflection of Andrew Carnegie's irrepressible intellectual curiosity—a lifelong quality clearly shown by his skilled biographer, Joseph Wall. Andrew Carnegie gave his trustees full freedom to change the purposes of the Institution, but in fact the Institution has evolved largely within the original mold. We remain Mr. Carnegie's institution for discovery, committed to leadership in investigation and to the discovery and support of the exceptional investigator.

In preparing letters to our alumni and friends several weeks ago, I searched my mind how best to convey the present character of our Institution. I recognized the risk in singling out a particular example of work in progress, but it seemed clear to me that our aspirations can be glimpsed in the research of Donald Brown and his collaborators at our Department of Embryology.

Brown's group asks what it is that causes a segment of DNA—a gene—to remain inactive on its chromosome until its coded message is needed for a specific role in the development of a complex organism. Their insights bring us closer to a molecular understanding of what I consider the central issue in biology: how the linear information in DNA can generate a specific three-dimensional organism during the course of development.

In the frog *Xenopus*, there are two families of 5S genes, genes required to build the ribosome, the protein-synthesizing apparatus of the cell. One class of 5S genes, the oocyte genes, are active only during a brief window in time early in embryogenesis and are then silent for the remainder of the life of the organism. This surge of 5S RNA is required early in embryogenesis to provide the growing egg with a large supply of ribosomes. In a series of elegant biochemical experiments, Brown has approached the question "What accounts for the activation of oocyte 5S genes in oocytes and the lack of their expression in somatic cells?" by reconstituting *in vitro* faithful developmental control of expression of this set of 5S genes. He then made the surprising observation that, unlike in bacterial genes, control of activity of the 5S genes is mediated through a DNA sequence which resides not adjacent to, but *within* the gene itself. This control region is the site of binding of a positive activator which "sits" on the DNA. RNA polymerase, which actually synthesizes the RNA product of the 5S genes, now binds not to the naked gene but to the gene complexed with control proteins. The complex is stable and the cycle is broken only later in embryogenesis when 5S RNA synthesis ceases and 5S RNA is diluted out of the growing embryo. This interaction of polymerase with a DNA-protein complex inside the gene, not with pure DNA, provides a novel solution to a problem in the control of gene expression and provides a conceptual framework for future thinking about similar gene control processes in other developing systems.

Many of the young investigators who have completed two- or three-year fellowships with Brown in recent years, now continue related investigations in their own laboratories elsewhere. In this way, Brown's laboratory is fertilizing a vital and growing field of inquiry. Meanwhile, formal recognition of the work expands: early this month, Brown shared the Louisa Gross Horwitz Prize, awarded annually by the trustees of Columbia University in recognition of outstanding basic research in biology or biochemistry. Coming soon after his Rosenstiel Medallion

(see page 125), the award establishes Donald Brown within a highly select, preeminent group among world-class investigators.

A Futuristic Note. Will the Institution's long-term future lead toward still closer ties among our several research centers? What is the proper place of astronomy in the Institution? Is the role of astronomy in the working out of future syntheses in the earth and planetary sciences sufficient to justify maintaining centers of astronomy on both coasts?

There are suggestions that the work at the Departments of Embryology and Plant Biology are growing together. In forefront genetics studies at Embryology, for example, it often is incidental whether the experimental organism happens to be "plant" or "animal." Meanwhile, the molecular tools usually associated with research in developmental biology are beginning to permeate nearly every basic investigation in the plant sciences. The questions that traditionally have guided work at the Department of Plant Biology—on photosynthesis and on mechanisms of adaptation—continue to do so, but they are now increasingly augmented on the molecular level, with techniques largely adapted from the pioneering work of developmental biologists studying other organisms.

In his provocative article, "Managing for Challenging Times: A National Research Strategy," Erich Bloch, Director of the National Science Foundation, has emphasized the nation's need to evolve more-cooperative relationships among scientific institutions, and to develop more programs that cross traditional disciplinary boundaries. Clearly our own recent decisions have anticipated Bloch's call for innovation in overcoming barriers that block cooperation without sacrificing the distinctiveness of the Institution. We must heed his caveat that new courses such as those upon which we are embarking will require changes in deeply ingrained attitudes. Unless we permit these changes to evolve, we risk destruction of a fragile enterprise.

James D. Ebert
December 19, 1985

The Year in Review

Department of Plant Biology staff. Seated at far left (listed from left to right): Mary Smith, Linda Roberts, Laura Green, Dow Woodward. Seated at far right: Malcolm Nobs, David Fork, Neil Polans. Front step: Lon Kaufman, John Gamon, Eugenio deHostos, Anne Bang, Peggy Lemaux, Pamela Conley, Jeanette Brown, Frank Nicholson. Second step: Robert Togaski, John Watson, Jerome Lapointe, Jeffrey Seemann, Dennis Greer, Joseph Berry. Third step: Arthur Grossman, Moritoshi Iino. Fourth step: Karen Hall, Carol Abdelhamid, Timothy Ball, Rudy Warren, Brian Welsh, Pedro Pulido. Fifth step: Susan Spiller, Aida Wells, Keith Mott. Standing: Norma Powell, Annette Coleman, Barbara Demmig, Einar Ingebretsen, Jake Levitt, Glenn Ford, William Thompson, Olle Björkman, James Shinkle, Tobias Baskin, Winslow Briggs.

The Year in Review

Ours is a time of vigor in science—an era of achievement made possible by recent decades of virtually uninterrupted scientific work worldwide. Research opportunities are unprecedented in every subdiscipline. The techniques of molecular biology, for example, are radically influencing wide areas of research in the biological sciences, opening the way for insights into questions scarcely envisioned not long ago. The new methods are showing how genes are controlled in higher organisms, how genes work together as families, and how cells synthesize and degrade regulatory products in response to their external environments. Molecular tools are bringing answers to older questions too—how plants adapt physiologically to environmental stresses, how their mechanisms of photosynthesis work, how evolutionary change proceeds.

Meanwhile in the earth and planetary sciences, excitement continues to grow from the discovery less than twenty years ago of the fundamental phenomenon of geotectonics: the creation, migration, and destruction of the Earth's great lithospheric plates. With this discovery, it became possible to view volcanism, seismicity, mountain building, continental evolution, and other geological phenomena with a global rather than a local perspective. Simultaneously, there is new ferment in astronomy—a product of the remarkable gains in observing power brought by charge-coupled devices (CCD's) and digital filtering techniques. The early frame for understanding and studying the galaxies built by Edwin Hubble and his colleagues fifty years ago remains useful, but its inevitable modification seems to be accelerating amid the remarkable insights of our times. A new generation of astronomers is beginning to command attention, and its members are exploring the germs of the syntheses that must surely lie ahead.

These developments will be manifest in our review of the Institution's scientific work, presented in the pages that follow. The text has been assembled from materials prepared by the directors and scientists in July 1985, and is intended to give readers who are not specialists in the particular scientific disciplines a sense of the Institution's current work. Our review, following custom, will focus on research in the year just ended. But it is worth pausing to note the

obvious—that the current research activities of individual scientists are, like the larger developments sketched above, products of achievements reaching many years into the past. Rarely if ever is a significant piece of research conceived, carried out, and interpreted in a single year.

Thus the significance of a given scientific investigation can be understood only in its relation to the universe of preexisting knowledge, questions, and methods. Indeed, every research venture builds on precedent, whether it seeks to test, refine, or extend an older frame or whether it points toward a more revolutionary outcome. Each discovery of new knowledge, each invention of theory, each development in instrumentation is both culmination of past understanding and prelude to a new beginning.

Given the essential continuity of inquiry, then, it would be hazardous to interpret a single year's work in historical isolation. Here and there in the essay that follows, therefore, we present the current research in broader perspective than might be expected. Although what emerges remains a relatively narrow view of selected work at a single research institution, we hope that the reader will recognize a series of snapshots which taken together demonstrate the continuity of the scientific endeavor. We shall glimpse competing interpretations at play, members of different specialties approaching common problems from opposite directions, the emergence of new theories and the refinement of earlier ones. Detectable will be that testing of ideas, that drive to obtain new and better data, that urge to work toward new syntheses, all of which mark the scientist as professional.

In short, we will witness the process of science—a never-ending flow driven by the scientist's curiosity, rigorous questioning of data, and originality in conceiving pathways to plausible answers.

The Biological Sciences

> Science . . . proceeds by detailed experimentation on limited areas of nature. It looks for partial and provisional answers for certain phenomena that can be isolated and well defined.
>
> François Jacob
> *The Possible and the Actual*
> 1982

Carnegie biologists over the years have developed numerous techniques of *in situ* experimentation. They have reconstructed the working environments of genes of higher organisms. They have developed means for following molecules directly inside living

cells. They have found ways to probe deeply into the inner workings of the photosynthetic machinery.

In this work they use experimental systems that range from a set of genes in the fruit fly, to the chromosomes of protozoa, to a genus of tropical pepper plants. Each one of these experimental systems carries with it the implicit assumption that what is learned will apply to wider areas in biology, perhaps even to agricultural or medical problems such as increased plant productivity or the cure of birth defects.

At Carnegie, though, the emphasis is—and always has been—on understanding the basic processes of life. As such, Institution scientists have traditionally shown little inhibition in crossing disciplinary or departmental boundaries. During the 1950s, for example, Philip Abelson initiated pioneering biogeochemical experiments at the Geophysical Laboratory—work continuing to the present day and this year expanding to include collaborative research with biologists at the Department of Plant Biology. At the Department of Terrestrial Magnetism, in an effort organized in 1947, another group of scientists began applying principles of physics to biology, often using radioactive materials as tracers in biological experiments. Pioneering work by Roy Britten and colleagues brought new techniques for DNA hybridization. Though the work was later discontinued at DTM, it is today reflected in studies of gene and cell function at the Departments of Embryology and Plant Biology, and at the Kerckhoff Marine Laboratory, where Britten is now a Carnegie staff member.

How Does a Gene Work? Transcriptional Complexes and Gene Control

> In my view, developmental control of genes is going to boil down to some very mundane biophysical principles.
>
> Donald Brown
> *Science 226* (1985), p. 1408

Only forty years ago, geneticists could not tell from which part of the chromosome—the proteins or nucleic acids—the genes were made. Most attention focused on the more complex proteins. But when it was discovered that the genetic instructions were encoded in the nucleotides of DNA, all attention shifted to the nucleic acids. Today, attention is returning, full circle, to the proteins. For it is becoming increasingly clear that proteins in the chromosomes of higher organisms play key roles in the regulation of genes; many genes seem to be turned on by the formation of highly specific and very stable protein-DNA complexes. At the Department of Embryology, director Donald Brown and staff member Steven McKnight study how these transcriptional

complexes may work in genes of higher organisms. Meanwhile, at the Department of Plant Biology, William Thompson examines the possibility that similar transcriptional complexes regulate the expression of plant genes.

Xenopus Ribosomal Genes. Donald Brown has spent over twenty years in pursuit of the control mechanisms that turn genes on and off during development. As a model system in this effort, he uses closely related 5S ribosomal RNA genes of the frog-like *Xenopus*. With his colleagues he has developed powerful techniques for probing these genes. One of the most notable was a method to study single working 5S RNA genes in an extract of *Xenopus* oocyte nuclei that simulates the gene's natural environment. (Oocytes are maturing egg cells.) Using this technique, Brown discovered five years ago that the control region for the gene (the region that is necessary for function) lay in the middle of the gene, within its coding sequence, and not on one of its ends, where control regions of bacterial genes lie. This year, still on the trail of *Xenopus* gene control, Brown and his current colleagues propose a mechanism for 5S RNA gene expression that they suggest may account for other examples of gene control among closely related genes.

5S ribosomal RNA genes encode the smallest of the three major RNAs needed to make ribosomes, the organelles in a cell where protein molecules are assembled. (Genes make proteins by first making templates of themselves, messenger RNAs, in a copying process called transcription. The mRNA of each gene exits the nucleus and travels to the ribosomes, where it is "translated" into protein precursors—the amino acids.)

The thousands of 5S ribosomal genes present in each *Xenopus* cell exist in two categories. One category contains about 98% of the total and is transcribed into 5S RNA only in oocytes. These genes are called oocyte 5S RNA genes. The genes in the second category, the remaining 2%, are called somatic 5S RNA genes. These genes, which differ slightly in structure from the oocyte 5S RNA genes, are transcribed in all cells, both egg and somatic. From a developmental perspective, it makes sense that more 5S RNA genes are transcribed in oocytes, for the egg's rapid growth to maturity requires the formation of enormous amounts of ribosomes. These ribosomes are stored for use by the developing embryo. Thus, the oocyte needs many more copies of the 5S RNA gene than does a somatic cell. But what, Brown wondered, are the mechanisms that turn off oocyte genes in somatic cells and turn them on in oocytes?

The DNA of higher organisms, unlike that in bacteria, is bound with protein. For some years it has been thought that interactions of proteins with genes plays a major role in gene regulation, but very little has been understood exactly how. Within the last two

years, Brown and his colleagues have illuminated this picture considerably. They have found, in 5S RNA genes, that a particular protein factor, TFIIIA, appears to be required for gene activity. TFIIIA functions by binding to the center of the gene (the gene's control region), nucleating the formation of a "transcription complex." Also bound stably to the complex are at least two other factors, none of which have yet been characterized. The complex thus formed—gene, TFIIIA, and the unidentified proteins—is so stable that many rounds of RNA can be made from it. Brown believes that the stability results from the cooperative nature of the binding: the proteins are bound not only to the gene but also to each other.

Knowing that an active gene is bound into a transcriptional complex, the developmental question, Brown writes, can be rephrased: Why are both oocyte and somatic 5S RNA genes found in active transcription complexes in oocytes while only somatic 5S RNA genes are in such complexes in somatic cells? The properties of TFIIIA itself suggests an answer. Brown and his colleagues have found that TFIIIA binds more tightly to somatic 5S RNA genes than it does to oocyte 5S RNA genes. Furthermore, they have found that much more TFIIIA is present in oocytes, where all 5S RNA genes are active, than in somatic cells, where the oocyte 5S RNA genes are repressed.

During the report year, Brown's group confirmed the importance of these properties in regulating expression of the gene. A slight difference in binding affinity, they found, is amplified into a large difference when the TFIIIA concentration is low. In their experiments, they injected cloned oocyte and somatic 5S RNA genes into cleaving embryos. The somatic 5S RNA genes were transcribed as much as 200 times more efficiently than were oocyte 5S RNA genes. This difference was promoted solely by the binding of TFIIIA. In additional experiments, they found that by injecting purified TFIIIA into embryos, they were able to increase the expression of the oocyte 5S RNA in somatic cells. This is the first instance, Brown writes, where a purified protein factor has been shown to activate a gene in a living cell.

Brown's work provides one of the most detailed examples to date of how a gene functions in a living, working cell of a higher organism. It may be that his results are of general significance; scientists may find that most genes in higher organisms are regulated by variations in binding affinity for specific transcription factors.

The HSV tk *Gene.* Embryology staff member Steven McKnight, like Brown, studies the transcription machinery of living cells, but he does so indirectly; he examines viruses. Viruses contain DNA but they lack most metabolic machinery; they can thus reproduce only when present inside a host cell. Once a virus has

infected a cell, it exploits the cell's transcriptional machinery by directing it to express viral genes and, in turn, make more copies of virus.

Certain viruses, like the mammal-infecting viruses that McKnight studies, further use regulatory products encoded by their own chromosomes. McKnight is interested in how the products of these viral regulatory genes selectively influence gene expression. From the results, he hopes to gain insight into the normal mechanisms of transcriptional control in mammalian cells.

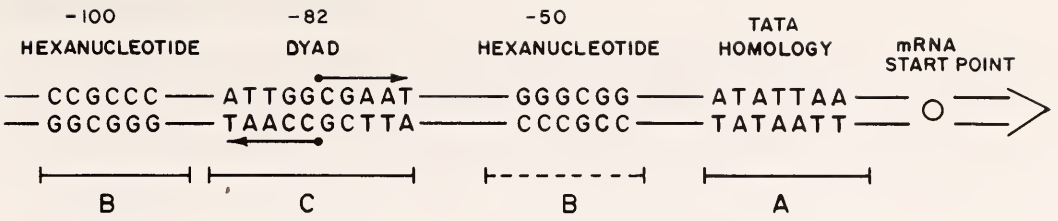
He is particularly familiar with the regulation of a gene encoded by herpes simplex virus—the thymidine kinase, or *tk*, gene. He first isolated and characterized the *tk* gene several years ago at the Department of Embryology. (McKnight was a postdoctoral fellow and staff associate at the Department from 1977 until 1981.) He found the *tk* gene to be small, only 1308 nucleotides long, and particularly amenable to molecular dissection. Following a technique developed by Brown for the *Xenopus* 5S RNA gene (*Year Book 78*, p. 75), he then determined that a small region beginning about 105 base pairs upstream from the transcription start point was required for the gene's proper expression.

In 1984, after spending three years at the Hutchinson Cancer Research Center in Seattle, McKnight returned to the Department as a staff member. There, with postdoctoral fellows Barbara Graves and Peter Johnson, he continues to study aspects of *tk* gene control. Last year, the group succeeded in identifying four subdomains within the gene's control region. Each one, they found, was characterized by a specific arrangement of nucleotides.

McKnight thought that the small subdomains might serve as binding sites for specific transcription factors, and that the binding would facilitate expression of the gene—much as Brown found to be the case with the 5S RNA gene. To explore this idea, he and his colleagues isolated several proteins from mammalian nuclei and tested them for binding affinity to the four *tk* control domains. So far, they have tentatively identified transcription factors that bind with, or "footprint," three of the four subdomains.

The results raise a host of questions for McKnight and his coworkers. Do the transcription factors that bind to the *tk* control regions also operate on the genes of the host cell? What do the factors do when bound to a transcriptional control region—do they stay stably attached to the DNA during transcription or do they cycle on and off with each round of activity?

Wheat and Pea Ribosomal Genes. While McKnight pursues these questions in Baltimore, William Thompson and his colleagues at the Department of Plant Biology in Stanford, California, investigate related questions in plants. Their goal is to reconstruct the chain of events leading to the activation of previously inactive plant genes.



Map of the control region for the herpes simplex virus, thymidine kinase (*tk*) gene, as determined by Steven McKnight and his colleagues at the Department of Embryology. This region of DNA, located within 105 nucleotides upstream from the transcription start point, contains four distinct subdomains, of which two—designated B—share a common structure. Subdomain A has an AT-rich "TATA homology." Common to many eukaryotic-coding genes, TATA homology appears to be critical for establishing the precise location of the mRNA start point. The subdomains B are GC-rich hexanucleotides, one on either side of subdomain C, which exhibits a dyad symmetrical structure. McKnight has found that the integrity of each of the four subdomains, which serve as binding sites for specific transcription protein factors, is required for expression of the *tk* gene. Both subdomains B bind the same protein.

It was only five years ago that Thompson, in collaboration with Carnegie research associate Michael Murray and Steven Spiker (then at Oregon State University), showed—for the first time—that active plant genes (those making mRNA) exist in a DNA-protein conformation unlike the DNA-protein conformation of inactive genes. This difference was revealed by an increased sensitivity of the DNA-protein conformation in the active genes to DNase I, an enzyme that degrades DNA where it is not protected by chromosomal proteins.

During the past year, Thompson and his colleagues, using as a model system the ribosomal genes of pea and wheat, found that an active ribosomal gene is more sensitive to DNase I in some regions than it is in others. The initial observation came out of Thompson's work with wheat plants, which he did in collaboration with Richard Flavell of the Plant Breeding Institute in Cambridge, England. Similar observations were soon made for the ribosomal RNA genes of pea plants by Lon Kaufman and John Watson in Thompson's group. (Kaufman is a research associate, Watson a postdoctoral fellow at the Department.)

Specific, localized sites of sensitivity to DNase I—"DNase hypersensitive sites"—had never before been reported in plant genes, though for many years they have been known to exist in animals. In animal genes, they appear to be correlated with gene activity, or potential for activity, and probably reflect localized alterations in DNA-protein conformation associated with, for example, the binding of specific proteins required for transcription.

In both pea and wheat, Thompson *et al.* have found that DNase hypersensitive sites exist not only in the ribosomal genes themselves but also in certain subrepeat DNA sequences present in several copies within regions of non-protein-coding ("spacer") DNA nearby. Furthermore, they have found—in what Thompson calls perhaps the most exciting observation to date—that

the distribution of DNase hypersensitivity sites, at least in pea plants, changes during development of the plant. Flavell and Thompson have proposed a model for ribosomal gene regulation in which certain sequences in the spacer region function as "enhancers." As such, these enhancers may attract various protein factors necessary for active transcription of the nearby gene; the binding of these factors to the chromosome may cause the distribution changes in DNase I hypersensitivity.

Methylation, Light, and Gene Control. In seeking further insight into the question of how plant genes turn on and off during development, Thompson has studied for several years a DNA modification process called methylation. A prominent feature of plant DNAs, methylation is the chemical attachment of methyl groups to cytosine (a nucleotide of DNA) in certain regions of a gene. In both animals and plants, methylation occurs more often in functionally inactive, or turned off, genes than it does in genes that are active.

Last year, Thompson and his colleagues found evidence that, in a single plant, levels of methylation differ in bud, leaf, and root cells. This year, in experiments designed to study the influence of light on methylation, Thompson, Watson, and Kaufman extracted the ribosomal DNA from different cells of seven-day-old peas grown either in darkness or in darkness with various exposures to white light. They located the methylation sites with the use of restriction enzymes known to be sensitive to methylated DNA. In all, they mapped 23 methylation sites in 90% of the ribosomal DNA. The results indicated that the DNA from buds was more heavily methylated than that from roots or leaves of the same plants and, further, that methylation decreased gradually during light-regulated leaf development. In plants that were exposed to three days of white light and then returned to darkness, the methylation level was similar to that of plants receiving seven days of light. Thompson concluded that once the change in methylation level had progressed for three days, the presence of light was no longer required for full manifestation of the response.

Ribosomal genes are present in two regions, or loci, in pea DNA. In one locus they are short, in the other they are long. Thompson and colleagues have found several differences between the long and short genes. For one, methylation seems to occur primarily in the short genes, and primarily at those sites thought to be responsible for transcriptional regulation. Also, short genes evidence many more changes in the distribution of hypersensitivity sites. (Long genes contain hypersensitive sites, but they do not appear to undergo changes during development.) Of even more interest, changes in the distribution of DNase hypersensitivity were found to occur at many of the same sites in the short genes where methylation was also found to occur. Just

upstream from the start site of transcription of a short ribosomal gene, for example, they located an area where hypersensitivity appeared and methylation decreased during light-induced leaf development.

On the basis of these observations, Thompson *et al.* propose that only one of the two loci—the one containing the longer ribosomal genes—is active in dark-grown cells. As development proceeds and the plants are exposed to light, the locus containing the shorter genes becomes active as well.

Gene Families: The Orchestration of Control

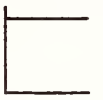
> Over the last several years we have been laying the groundwork for what we hope will become a system for studying the coordinated response of many genes during light-induced development. . . .
>
> William F. Thompson
> Department of Plant Biology
> July 1985

Genes function as parts of systems of genes whose orchestration requires complex coordination. For a complete picture of how development proceeds in an organism, it is necessary to understand how this coordination works at the molecular level. Do mechanisms of control, for example, depend on certain arrangements of genes along the chromosomes? Do related genes have to be located in the same region of the genome—or can they be in different places? Questions like these, more and more, occupy the time and thoughts of developmental biologists at the Departments of Embryology and Plant Biology.

The mRNA Response. Thompson's experiments on the developmental regulation of individual ribosomal genes, described above, are yielding valuable insights into gene control in plants. But they were also designed, Thompson writes, as test runs for experiments on genes involved in the coordinated responses of many genes during light-induced development. In this larger study, which has recently included collaborative work with Winslow Briggs, Thompson *et al.* focus on many different genes rather than on one or two. While studying one or two genes would be much simpler than studying ten or more, Thompson notes, it would have prevented them from seeing the diversity of molecular responses they felt were probably involved in complex developmental changes.

The work began several years ago with the isolation of cDNA clones from thirteen different messenger RNAs in pea whose concentration changes during growth in the light. The precise conditions required to induce these changes and the details of the responses have been, since then, a major focus of Thompson's lab.

This year, the group classified the mRNA responses into several broad categories, mainly according to the time course with which they occur. Thompson notes, however, that there is still much variation within each category. (See table, below.)

GROUP	CLONE	COPY NUMBER	TIME COURSE	FLUENCE RESP	PLUS WHITE	RECIP	WHITE	BLUE	AUXIN	CONT RED
IA	pAB96	6–12		VLF,LF	LF	Y	INC	N	N	Y
IB	pSS15	6–12		LF	LF	Y	INC	Y	Y	N
	pEA25	1–2								?
	pEA238									N
	pEA303									N
IC	pEA214			LF	–	Y	INC	Y	Y	N
	pEA277	1								
IIA	pEA46	1		LF	–	Y	INC	Y	Y	N
IIB	pEA315			LF	LF	Y	INC	Y	Y	Y
IIIA	pEA170			VLF	LF	Y	DEC	N	?	?
IIIB	pEA215	1		LF	VLF,LF	Y	DEC	Y	Y	Y
IV	pEA13	1		–	–	N	INC	N	?	?
V	pEA207	3–6		–	–	Y	DEC	N	N	N

As part of a study examining the developmental expression of related plant genes, William Thompson and his colleagues at the Department of Plant Biology have isolated cDNA clones corresponding to thirteen messenger RNAs in the pea plant. Above, these thirteen cDNA clones are grouped according to their responses to light. Column marked FLUENCE RESP indicates light response of clones exposed to a single pulse of red light. Column marked PLUS WHITE indicates response of clones exposed to a single red pulse and an additional 24 hours of white light. Column marked RECIP indicates whether responses showed reciprocity between fluence rate and duration of irradiation. Under column marked WHITE, increases or decreases in abundance after treatment with white light alone are noted. Under column marked BLUE, responses to blue light after continuous red irradiation are noted. Column marked AUXIN shows responses to auxin treatment, and column marked CONT RED shows whether or not mRNA transcript levels were higher to auxin treatment following continuous red light treatment than they were to a single pulse of red light.

Although showing great diversity of mRNA response to light, even within a single category, the table provides a base upon which Thompson and his colleagues can examine responses to light at the molecular level.

Abbreviations: LF = low fluence response; VLF = very low fluence response; — = no response; INC = increase; DEC = decrease; Y = yes; N = no; ? = inconclusive evidence.

Thompson's group also began an effort this year to obtain clones from the genes encoding the thirteen mRNAs. Unlike the cloned DNA copies of the mRNAs, the clones of the actual genes contain surrounding DNA sequences. Such surrounding sequences in working chromosomes are known in many instances to be critically involved in regulating gene activity.

So far, Thompson and Watson have obtained several clones of two sets, or families, of genes whose mRNA they have studied. One family, called *cab*, contains about six genes that code for chlorophyll-binding proteins critical to the proper functioning of photosynthesis. The genes in the other family, *rbcS*, code for the small subunit of an important plant enzyme (RuBisCO; see p. 42) involved in photosynthesis.

It appears that within the general category of a single family, individual genes may be regulated differently. Kaufman and Thompson (in collaboration with N.-H. Chua of Rockefeller University) found, for example, that different *rbcS* genes do not respond identically during the first 24 hours following a single red light treatment. It is an intriguing possibility, Thompson notes, that similar differences in the response of individual genes in a gene family might account for the two-component red light fluence response curve they found for *cab* RNA last year (*Year Book 83*, p. 17). They have begun an effort to analyze genomic clones of different *cab* genes (in collaboration with Bruce Roe of the University of Oklahoma), but in their current assays they cannot yet distinguish the RNA products of different genes.

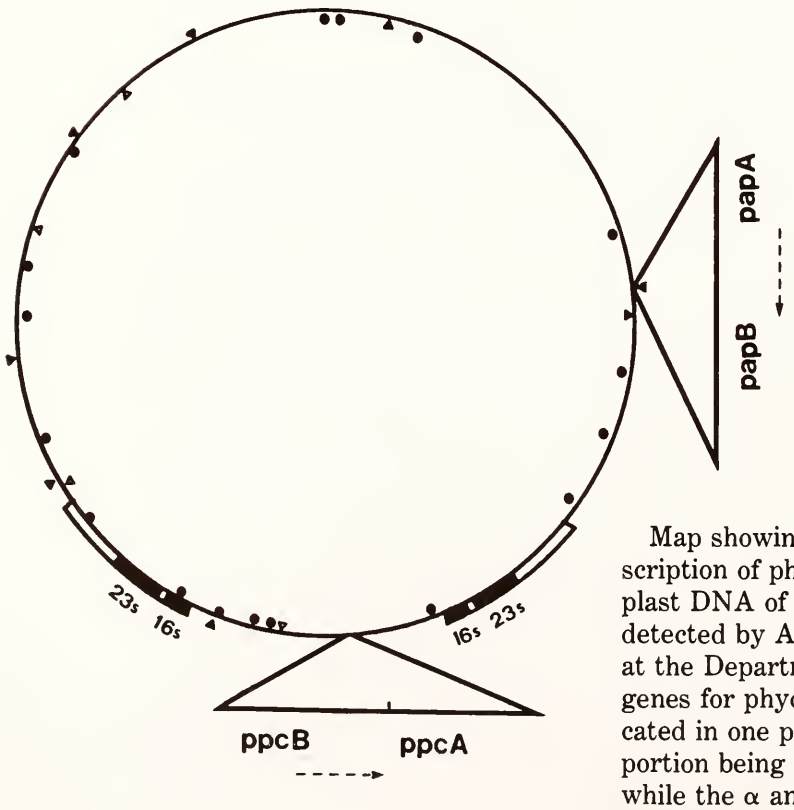
In a related study, with Norman Weeden of Cornell University, Thompson and postdoctoral fellow Neil Polans have found that the *rbcS* and *cab* gene family members exist in clusters, and that each cluster is located on a different chromosome; the *cab* genes are located on chromosome 2, the *rbcS* genes sit on chromosome 5. Since both gene families code for proteins intimately associated with photosynthesis, they must be expressed with some degree of coordination during development of the photosynthetic apparatus. In whatever way that coordination is achieved, notes Thompson, it must not depend on the close physical proximity of the genes on a chromosome.

Phycobilisome Gene Organization. Physical separation is the case, also, for some genes in red algae that code for different components of the phycobilisome system. Phycobilisomes are unique light-harvesting complexes found in red algae and cyanobacteria. They are composed of stacks of pigment proteins (phycobiliproteins) linked together by colorless proteins (linkers) in an orderly array.

Arthur Grossman, a Plant Biology staff member who studies phycobilisome genes, has found that, in red algae, the genes that code for the phycobiliproteins are located in the chloroplast, while the genes encoding the linkers are located in the nucleus.

(The chloroplast is a small DNA-containing body within the cell.) This arrangement may reflect the evolutionary transfer of genes from the chloroplast to the nucleus, a possibility that reflects, in turn, a still unproved hypothesis that the chloroplast is itself an evolutionary descendent of once-independent cyanobacterium. Incorporated into unicellular protozoa, the engulfed cyanobacteria may have gradually lost their genetic potential to their host nuclei.

In both red algae and cyanobacteria, the phycobiliproteins make up some 85% of the phycobilisome complex, and occur in three major varieties—phycocyanin (PC), phycoerythrin (PE), and allophycocyanin (APC). Each one of these components contains an α and a β polypeptide subunit. Last year, Grossman and one of his colleagues, research associate Peggy Lemaux, isolated the gene encoding the β subunit of PC (ppcB) from the chloroplast of the algae *Cyanophora paradoxa.* This year, Grossman and Lemaux isolated the α subunit of the PC gene (ppcA), as well as both α and β genes of APC. (They could isolate APC subunits so quickly because homology exists between all phycobiliprotein subunits at the amino acid level; thus it was possible to use the isolated PC subunit genes as probes.) They found that the ppcA gene was situated right next to the ppcB gene. The APC genes, however, were in a different region of the chloroplast genome entirely.



Map showing the location and direction of transcription of phycobiliprotein genes in the chloroplast DNA of the alga *Cyanophora paradoxa.* As detected by Arthur Grossman and his colleagues at the Department of Plant Biology, the α and β genes for phycocyanin (ppcA and ppcB) are located in one part of the genome (with the ppcB portion being transcribed first—see arrow), while the α and β units of allophycocyanin (papA and papB) are located in another region. Other marks along circle indicate restriction enzyme cuts in the DNA. Widened areas along bottom of map represent inverted repeat regions which encode the 16S and 23S ribosomal RNAs.

In an effort to analyze the transcription of the PC and APC genes in *C. paradoxa*, Grossman and Lemaux this year sequenced parts of the coding and regulatory regions. They found that both subunits of PC are translated from a single mRNA molecule, and that the two subunits of APC are translated from another mRNA. This mode of transcription, Grossman notes, may ensure that the polypeptide subunits of each phycobiliprotein are synthesized in equal amounts.

Grossman, Lemaux, and postdoctoral fellows Pamela Conley and Terri Lomax, in collaboration with J. Schilling, a research scientist at Calbiotech in Mountain View, California, have also done studies on the arrangement, structure, and function of phycobilisome genes in cyanobacteria. Cyanobacteria are much more primitive than red algae; they do not contain chloroplasts, and their genomic DNA is not surrounded by a membrane. Yet the phycobilisome system in these organisms exhibits an interesting variation: it can modulate its constituent polypeptides in response to the color of the light it receives. This "chromatic adaptation" reaction enables cyanobacteria to use effectively whatever wavelength of light is prevalent in their environment.

Cyanobacteria can be organized into three main categories, depending on responses of their phycobilisomes to light. Group I organisms synthesize constant levels of PE and PC, regardless of light color. In group II organisms, PE is regulated by light quality (with elevated levels in green light and reduced levels in red light), but PC is not. Group III organisms exhibit the most dramatic response. They show high levels of PC and low levels of PE in response to red light, but just the reverse in green light.

Because the phycobiliprotein genes in cyanobacteria are similar to those in red algae, Grossman and his colleagues were able to use *C. paradoxa* PC phycobiliprotein genes as probes in finding PC genes in the cyanobacterium *Fremyella diplosiphon*. They determined that both APC and PC phycobiliprotein genes in *F. diplosiphon* (a member of group III) are clustered in one region of the genome, and that transcripts (mRNAs) from all of these genes are present in large numbers in the cell. However, a transcript from one PC gene set is only present in cells that were grown in red light. In green-light-grown cultures, PC transcripts from this set of genes are absent.

In detailed examination of this light-regulated PC gene set, Grossman and colleagues found that the α and β PC genes are linked and are transcribed simultaneously as two mRNAs, one 1600 nucleotides, the other 3800 nucleotides in length. The short transcript encodes α and β PC subunits, while the long transcript encodes α and β PC plus a light-regulated linker polypeptide.

Organization of Genes in Roundworm Sperm. As Grossman pursues questions about the organization of genes and gene prod-

ucts in algae, Samuel Ward, at Embryology, studies similar questions about genes and proteins in the roundworm. Ward is particularly concerned with how cells differentiate during the complex pathways of development.

During development, individual cells must commit themselves to a particular function. They must produce specialized protein products designed for specialized uses. Further, they must arrange these proteins properly: phycobiliproteins must be arranged into stacks; muscle proteins must be arranged into parallel filaments; nerve proteins must be arranged into long, thin axons. Where in a cell, Ward wonders, are the instructions that specify protein arrangements? In viruses, most instructions for assembly are contained in the shapes of the proteins themselves; the molecules come together chemically much as atoms do to form crystals. Is this also true for cells? If so, what reads the instructions?

In addressing these broad and difficult questions, Ward focuses on a single simple cell—the sperm cell of the roundworm *Caenorhabditis elegans*. Since 1978, Ward and his colleagues have isolated and cloned more than fifteen different genes whose mutations affect sperm development. Some of these mutations disrupt the sperm's amoeboid movement. (Roundworm sperm do not have long tails but crawl like amoebas.) Other mutations alter the shape of the cell. Still others disrupt the sperm cell's normally asymmetric surface.

This year, Ward and members of his laboratory focused their efforts on the organization of the large family of genes that encode the most abundant proteins in the roundworm sperm. The family is large presumably because it enables the worm to make a large amount of proteins quickly during the short interval of sperm development. Ward and colleagues find that subsets of this family with similar sequences are grouped together in small clusters along several chromosomes. The clustering of the genes may have functional significance, Ward notes, perhaps related to their coordinate regulation, but it also may reflect the way the multiple genes arose by duplication during evolution.

Meanwhile, in related work, he and his colleagues have found that sperm of another species of roundworm, *Ascaris lumbricoides* (a major human and animal parasite) contains a major protein similar to that in *Caenorhabditis*. Postdoctoral fellow Karen Bennett used one of the *Caenorhabditis* genes to find the genes in *Ascaris* that encode this protein. Surprisingly, she finds that *Ascaris* contains only a single copy of the gene.

Ascaris has an interesting history. In the nineteenth century, scientists observed that chromosomal material was lost from early cells of *Ascaris* that would eventually become body cells. No chromatin was lost, however, from cells that would become sperm and egg. The zoologist Theodore Boveri proposed that the chromatin lost from body cells (in modern terms, the genes) would

Staff member Samuel Ward, graduate student Diane Shakes, and postdoctoral fellow Steven L'Hernault at the Department of Embryology.

contain substances needed only by sperm and eggs. Since the major sperm protein that Bennett isolated in Ward's lab is indeed specific for sperm, she was able to test Boveri's hypothesis. The result was unambiguous: the gene occurs in all cells, body and sex alike, and it is not rearranged in those cells that do not need it. It is just not expressed. Thus, at least for this gene, Boveri was mistaken.

Regulation of Chorion Gene Amplification. The fruit fly, once an organism of choice for generations of classical geneticists, has reemerged over the last two decades as a valuable experimental system in the laboratories of molecular biologists. At the Department of Embryology, staff member Allan Spradling uses *Drosophila* to probe the mechanisms that control the synthesis of eggshell protein.

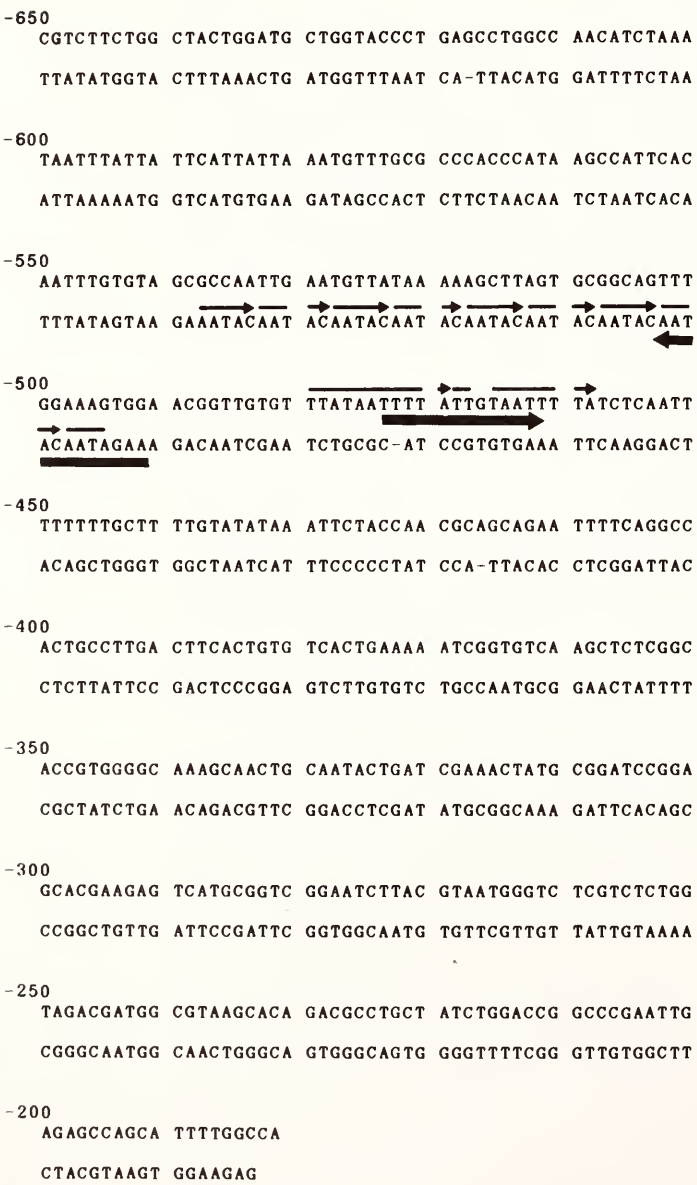
A female fruit fly produces eggs at an extraordinary rate, equal to more than half her body weight per day. Each egg that she lays is surrounded by a thin coat made up of six major types of protein. The genes responsible for producing these eggshell proteins, called chorion genes, are located in two clusters along the chromosomes. Each cell of a female fly contains just two copies of each chorion gene, with two genes in one cluster and four in the other. In most of her cells, these genes serve no use and are inactive. But in the ovarian cells, they are responsible for producing all the eggshell protein the adult female needs over a lifetime of egg laying. How can so few genes do this?

Twenty hours before the beginning of eggshell production, all the chorion genes in the ovary cell begin to amplify, or increase in number. This quickly leads to the production of from sixteen to

sixty additional copies of each gene. This process of gene amplification allows the female to produce an extraordinary amount of each chorion protein very quickly.

In studying how chorion genes work, Spradling uses a gene transfer technique that he developed in 1982 with then staff member Gerald Rubin. The two scientists found that genes ferried into a fruit fly embryo via transposable elements (naturally mobile pieces of the chromosome) would be incorporated stably in the germline. Spradling and his present colleagues use the technique to transfer mutant chorion genes into fruit fly embryos; they then examine the offspring to see if the genes are properly expressed.

From the results of their experiments, they have found that chorion genes are regulated by two sets of controls: one set tells the genes to amplify, the other tells them when and where to make protein. The amplification control region is shared by all the genes



DNA sequence of two regions of DNA (upper and lower sequence) in *Drosophila* that Allan Spradling and his colleagues at Embryology find essential for proper chorion (eggshell) gene amplification. The regions lie just upstream from major chorion genes and include repeated sequences (small arrows) near a common 12-nucleotide-long sequence (large arrrows). Spradling proposes that the common sequence lies within the origin, or "start site," of DNA replication used during amplification of each gene cluster. The numbers at left count nucleotides before the beginning of the associated chorion genes.

within each gene cluster, but each individual gene contains a separate region that controls protein manufacture.

Last year, Spradling and postdoctoral fellow Diane de Cicco determined that the amplification control region of one chorion cluster was confined to a sequence 3800 nucleotides long. This year, Spradling and postdoctoral fellows Terry Orr-Weaver, Barbara Wakimoto, and Laura Kalfayan found that only a small part of this sequence was actually required for amplification—one about 430 nucleotides long. An amplification control region was also defined, using the gene transfer method, within the second chorion gene cluster.

In each cluster, control sequences are located from 200 to 600 nucleotides upstream from a major chorion gene. Both regions contain repeated sequences near a similar 12-nucleotide-long sequence. Spradling speculates that this common sequence lies within the "origin"—the point where the DNA starts to replicate itself when making extra gene copies.

Very little is known about the structure and function of specific replication origins in the chromosomes of higher organisms. Indeed, the very existence of origins has been for years a matter of debate; some scientists believe that replication begins at random sites along the chromosomes. Spradling is hopeful that further elaboration of the chorion amplification control regions will eventually provide a model system for understanding, in general, how the origin of replication works in chromosomes of higher organisms.

Chromosome Organization during Development

Embryology staff member Joseph Gall is interested in the structure and function of chromosomes, particularly in ways in which chromosome activity affects development of the embryo. He studies chromosomes of maturing egg cells (oocytes) before fertilization because the products of these chromosomes control events during oocyte growth and early embryo development.

Oocyte chromosomes are known as "lampbrush" chromosomes, a name given them in the nineteenth century because of their fancied resemblance to the brushes used for cleaning lamp chimneys. Their brushiness is caused by hundreds of looped-out segments that are sites for very active mRNA synthesis. (See Frontispiece photo, p. 2.) In a few organisms, such as the newt and frog, the lampbrush chromosomes reach gigantic proportions—up to a millimeter in length. This permits a variety of molecular and microscopical studies that cannot be done on any other organism.

Gall and his colleagues focus their attention on a particular cluster of loops on newt lampbrush chromosomes that transcribe mRNA for histone proteins. (The histones are an important group of five proteins that are associated with DNA in the chromosomes.)

Their approach is to determine exactly which RNA sequences are transcribed when histone mRNA is being made. To do this, they use an *in situ* nucleic acid hybridization technique that Gall developed several years ago. In this technique, a radioactively labeled RNA or DNA probe (made in the test tube) is bound to complementary RNA molecules made by the oocyte itself on the lampbrush chromosome loop.

Gall and his co-workers have found that the histone loops synthesize not only the mRNA for the histone proteins, but, contrary to current models of gene transcription, they also synthesize RNA from other regions of the chromosome adjacent to the histone genes. In particular, the loops synthesize RNA from a region that contains a very simple, highly repetitive sequence known as satellite DNA. This was especially surprising, for it has been assumed for many years that such simple repetitive DNA sequences—whose function is yet unknown—are never transcribed.

Gall and his colleagues have since discovered other regions in lampbrush chromosomes of newt and frog where such simple repetitive DNA sequences are transcribed. They are attempting to understand what significance this unusual transcription may have in the egg cell.

Meanwhile, in other experiments, Gall's group is studying structural features of chromosomes, especially the very ends of chromosomes—the telomeres, which pose special mechanical problems during replication. Gall *et al.* hope to learn how the ends replicate and what special structures they possess. But because at the molecular level chromosomes are so large, and because most small DNA molecules produced by living cells are circular—probably to avoid the mechanical problems posed by replication—the group finds it more convenient in studying the telomere to analyze model systems instead. The model systems they use are small, linear molecules of protozoa.

One of these linear molecules is found in the nucleus of the protozoan *Tetrahymena*; another is found in the mitochondria of the fresh water *Hydra*. Gall and his colleagues are attempting to determine the nucleotide sequences at the ends of the *Hydra* molecule. Once they have done this, they hope to compare the sequences with sequences found at the ends of other linear molecules. In the case of the *Tetrahymena* molecule, they already know the end sequences. They are therefore concentrating on how the molecule replicates.

The Molecular Analysis of Geminiviruses

Geminiviruses are small, single-stranded plant viruses transmitted by either whiteflies or leafhoppers. One of them, Maize Streak virus (MSV), is transmitted by leafhoppers and, like other members of this subgroup of geminiviruses, infects a wide variety

of plants. Squash Leaf Curl virus (SqLCV) is transmitted by whiteflies and has a broad host range that includes squash and beans—a range that is uncharacteristically broad for a whitefly-transmitted geminivirus.

At the Department of Embryology, staff associate Sondra Lazarowitz uses the tools of molecular biology in her efforts to understand the life cycles and host ranges of MSV and SqLCV. She and her colleagues have succeeded in cloning the various DNA components of each. They have identified four distinct DNA components in SqLCV-infected plants, each about 3000 nucleotides long. Based on host range and a comparison of the DNA sequences of these four components with each other and with components from other whitefly-transmitted viruses (whose genomes typically contain not four but two distinct DNA components, i.e., bipartite), they have determined that SqLCV is two distinct but closely related bipartite whitefly-transmitted geminiviruses.

The genome of Maize Streak virus, in marked contrast, contains only a single 2700-nucleotide-long DNA component. This suggests to Lazarowitz that MSV represents what may be genetically a very simple geminivirus. Its molecular analysis has the potential, she says, of providing some exciting insights into mechanisms of gene expression in geminiviruses and, possibly, in plant cells. Furthermore, the molecular differences that separate the relatively simple MSV, with its wide host range, from the more complex genomes of the SqLCVs—one with a typically narrow host range, the other with a broader range—provide nicely juxtaposed systems for her study of viral determinants of pathogenesis and host range.

The Changing Genome

> To understand the evolution of species it appears that we will need to know the principal sources and kinds of genomic variation and the mechanisms or systems through which genomic variations affect genes, their expression and the phenotype.
>
> Roy Britten
> *Evolution and Development*
> J. T. Bonner, ed. (Springer Verlag)
> 1982

It is clear that as evolution proceeds, new species continually emerge from old; DNA mutates to form new gene combinations, the chromosomes move around to form new arrangements. Without these changes, organisms could not adapt to their changing environments, and life might long ago have become extinct. What is not clear, however, is exactly why, how, and how often these events occur.

Normal mechanisms of genetic recombination operate in most higher organisms; they ensure that each individual is slightly differ-

ent from its parents. But there are also other, yet poorly understood, mechanisms of genetic recombination whose actions serve to rearrange the genome in "illegitimate" ways. One such vehicle is the action of transposable elements. Transposable elements are movable pieces of DNA that were first discovered in maize about forty years ago by Barbara McClintock, a staff member at Carnegie's former Department of Genetics. McClintock found that maize elements could cause mutations to the genes and massive chromosomal rearrangements.

McClintock's discovery was not fully appreciated until the late 1970s, when scientists working at the molecular level began finding transposable elements in a wide range of organisms, from bacteria to man. At about the same time, Nina Fedoroff began an effort to characterize at the molecular level the maize transposable elements that McClintock had discovered using only genetic techniques. Today, Fedoroff continues this work at the Department of Embryology, where she is a staff member. Meanwhile, Roy Britten, a Carnegie staff member with a joint Carnegie-Caltech appointment at the Kerckhoff Marine Laboratory in Corona del Mar, California, examines what roles these movable elements, or their derivatives, may have played during evolution.

Transposable Elements in Maize. Nina Fedoroff and her colleagues last year isolated and sequenced the DNA of several elements in a two-element family of transposable elements in maize that McClintock called the *Activator-Dissociator* (*Ac-Ds*) family. This year, while continuing to study this family, they began the isolation of elements belonging to another, more complex family discovered by McClintock—the *Suppressor-mutator* (*Spm*) family.

McClintock found that in the *Ac-Ds* family, *Ds* can only transpose (move) when *Ac* is present. (*Ds* elements are most often defective derivatives of *Ac*.) In the *Spm* family, however, she found the genetic interactions between fully functional *Spm* elements and their defective derivatives (*dSpm*'s) to be more complex. She observed that while an *Spm* element is required for the movement of a defective element into a gene, the mutations promoted by this movement may not be complete. In those daughter cells that do not contain *Spm*, the mutations are "leaky," that is, they give only partial expression to the gene. An "invaded" purple pigment gene, for example, would still make pigment, but in a lighter shade.

When a functional *Spm* element is introduced into a genome that contains a leaky *dSpm*-mutated gene, however, that gene is suppressed, or turned off, entirely. Furthermore, because a functional *Spm* is able to promote the transposition of *dSpm* away from the mutated gene, the gene can revert, or back-mutate, to normal function. Functional *Spm* elements thus behave genetically as if they have two distinct functions—a "suppressor"

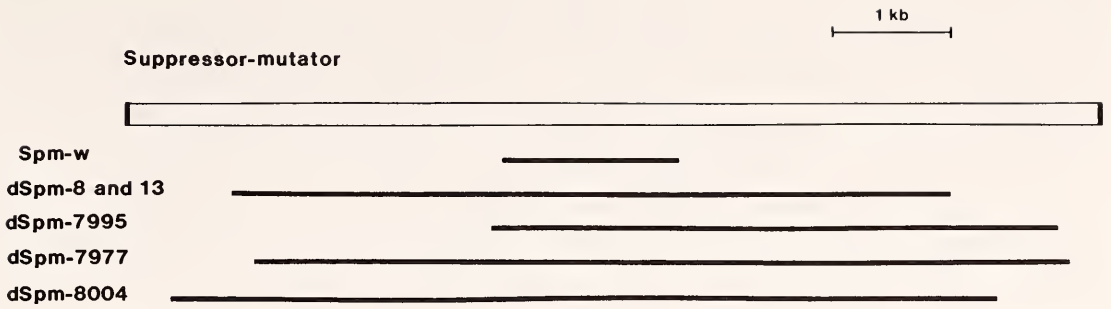


Diagram of the maize Suppressor-mutator (Spm) transposable element (open bar) that Nina Fedoroff and her colleagues at the Department of Embryology isolated during the report year. The dark bars indicate what portions of the intact element are missing in several isolated mutant Spm elements. Spm-w has an internal deletion of about 1600 nucleotides near the center of the element. The elements designated dSpm-7995, dSpm-7977, and dSpm-8004 have more-extensive deletions, encompassing half or more of the intact element. The small deletion in Spm-w alters the expression of the transposition function, while the larger deletion in the right half of the dSpm-7995 abolishes it entirely. Fedoroff thus believes that the transposition control function is encoded in the element's right half.

function and a "mutator," or transposition, function.

Fedoroff is curious to know how this dual function works on the molecular level. She and her colleagues this year isolated and analyzed one fully functional *Spm* element and several defective derivatives. The functional element is about 8200 nucleotides long and appears indistinguishable from the genetically similar *Enhancer* element isolated last year in H. Saedler's laboratory at the Max Planck Institute in Germany. The defective elements have extensive deletions encompassing half or more of the intact *Spm* element. Fedoroff *et al.* found that a small 1600-nucleotide-long deletion in the middle of one of the elements caused an altered transposition function; the element was able to excise from a locus, but it did so late in development and less frequently than the intact element. Another defective element had a larger deletion overlapping the 1600-nucleotide segment and extending nearly all the way to the end of the right side. The functional result was that this element could not transpose at all. It appears, then, that the element's transposition function is encoded in the right half of the element. This adds confirming evidence to Saedler's previous finding that the right half of the intact *Enhancer* element encodes an RNA transcript; it is likely, therefore, that this transcript encodes the element's transposition function.

Evolutionary Rearrangements of DNA. Barbara McClintock found that maize transposable elements could promote reversible gene mutations in regular patterns throughout development. But there is little evidence that these movable elements perform such

controlling functions in other organisms. In fact, no purpose has yet been assigned to transposable elements. All the same, many scientists—including Roy Britten—believe that these movable pieces of DNA, by their very presence in the genome, may have profound effect over evolutionary time.

As a staff member of Carnegie's Department of Terrestial Magnetism during the 1960s, Britten found that some sequences of DNA—those with no gene-coding functions—existed in higher organisms in thousands, even millions of copies per genome. He speculated at the time that these repeated sequences were involved in the regulation of genes. Since then, he has come to believe that changes to these non-coding sequences—of the sort promoted by transposable elements—could affect gene regulation and thus more profoundly affect species evolution than changes to the genes themselves.

For many years, Britten and his colleagues at Kerckhoff have been using DNA hybridization techniques to compare the DNA of various sea urchin species known to share common ancestors. They have found that repeated sequences in the sea urchin genome have been rearranged a great deal during evolution. This year, in related experiments on the genomes of chimpanzees, gorillas, orangutans, and man, they found evidence that repeated sequences in the primate genome have also been much rearranged. Two widely interspersed repeat families—KpnI and Alu, which make up several percent of human DNA and which may be transposable—have gained or lost at least half of their individual interspersed repeats during evolution of the higher apes.

The majority of the genome in higher organisms is made up of non-coding, single-copy DNA whose sequences appear to undergo neutral drift during evolution. (Drift rate—the substitution of one nucleotide base for another—is a good measure of the underlying mutation rate.) The small fraction of the DNA that codes for genes changes much more slowly than the non-coding DNA. This is presumably the result of selection against changes in the encoded proteins.

Britten has assembled from the published literature a set of nearly fifty interspecies comparisons of DNA sequences for cases where some estimate of the divergence time of the lineages could be made. His data show that the rate of mutation differs significantly between species. Among sea urchins, rodents, and some insects, the drift rate averages 0.66 per cent per million years. In primates and birds, the rate averages 0.15. It appears that the mutation rate among primates slowed considerably at about the time the lineages leading to the lower and higher primates diverged. Britten believes that this knowledge may have a significant influence on future evolutionary models.

Membranes: Interaction, Communication, Regulation

> The composition of the plasma membrane determines to a large extent what signals are perceived by each cell and what responses each cell type can make.
>
> Douglas Fambrough
> Department of Embryology
> July 1985

Biological membranes consist of a semi-fluid, two-layer film of proteins, glycoproteins, and lipids. These ultrathin but ultrastrong structures play important roles in and among cells. The outer, or cell surface, membrane is each cell's interface with other cells and the extracellular fluids of the organism. It directs traffic into and out of the cell and communicates with nearby cells to regulate the complex interactions accompanying growth and development. Membranes are also found inside cells, where they surround and protect each separate organelle.

Carnegie scientists study membranes using a variety of techniques and a variety of biological systems. At the Department of Embryology, Richard Pagano studies lipid transport in hamster cells, Douglas Fambrough studies the sodium pump on nerve and muscle membranes in chick cells, and Martin Snider investigates the roles of cell surface receptor proteins in mammalian cells. Meanwhile, at Plant Biology, Arthur Grossman has begun an effort to examine how the plasma membranes surrounding algal cells regulate nutrient uptake.

Membrane Lipid Traffic in Animal Cells. Members of the laboratory of Richard Pagano have developed methods for studying lipid transport in cells using fluorescent analogs of natural lipids. It is thereby possible to examine the movements of lipid molecules in living cells by fluorescence microscopy and to correlate these observations with classical biochemical investigations. Some examples of the approach have been discussed in previous Year Books. Highlighted here is postdoctoral fellow Paul Uster's development of a technique called resonance energy transfer (RET) microscopy. The method greatly enhances the apparent resolution of the microscope and will allow the investigators to carry out certain experiments on lipid transport and distribution in cells which, until now, have not been possible.

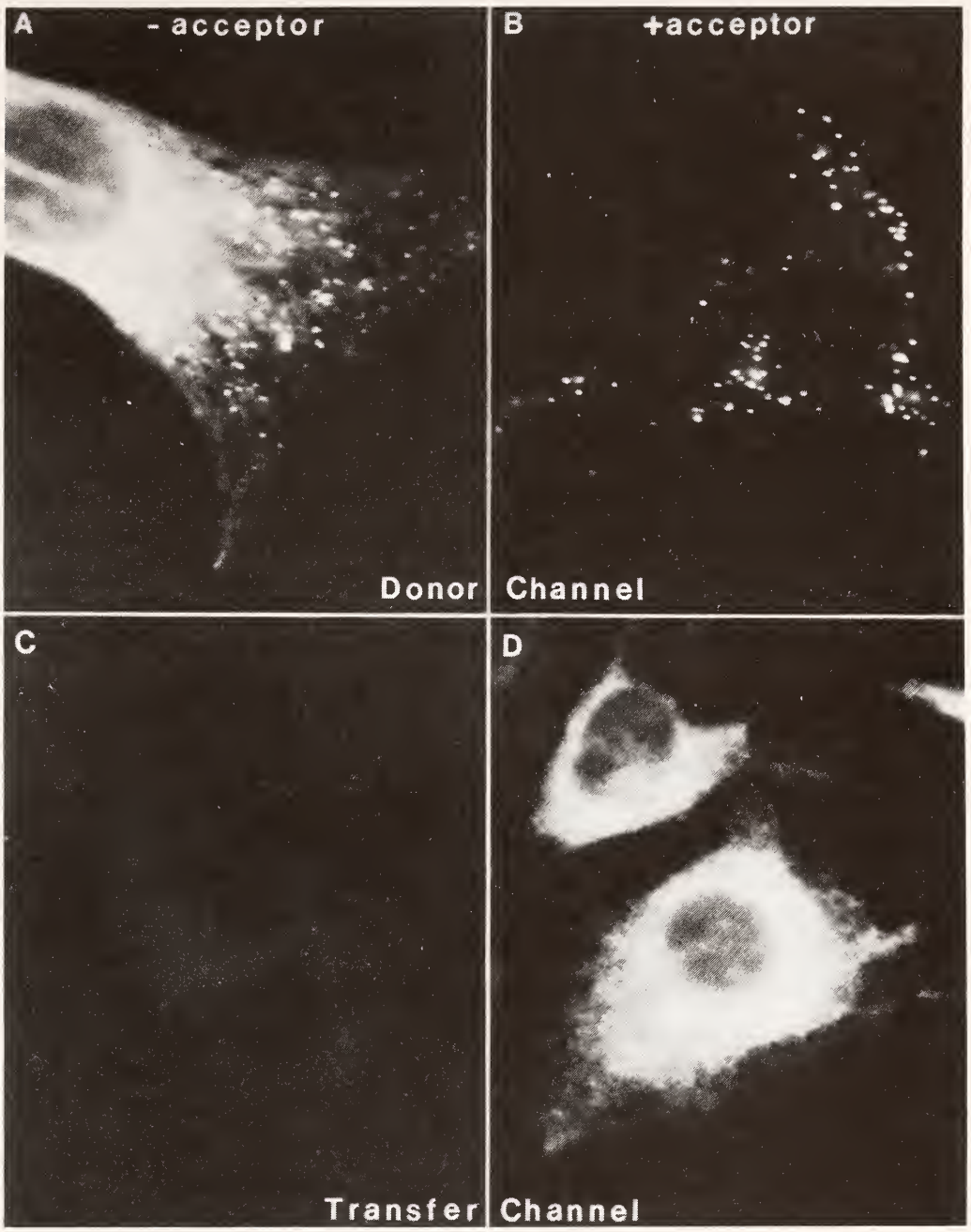
RET relies on the interactions which occur between two fluorescent molecules if the emission band of one, which serves as the energy donor, overlaps the excitation band of the second, the

energy acceptor. When these conditions are met, the energy from a photon absorbed by the energy donor can be transferred to the energy acceptor. This results in dramatic quenching of the donor's fluorescence and an enhanced emission of the energy acceptor, which then fluoresces as if it had been excited directly. Because RET decreases in proportion to the inverse sixth power of the distance separating donor and acceptor, it is only detected when these molecules are very close together.

RET had been used in many systems as a "spectroscopic ruler" to measure distances between and within molecules. Most of these studies have been carried out in solution, using a conventional fluorimeter to measure fluorescence. However, to the knowledge of the investigators, RET has not previously been used as a visual, microscopic tool. Since the resolution of light microscopy is a few tenths of a micron, while the distance over which RET is effective is much less ($\leq$100 Å), Uster and Pagano reasoned that it should be possible to enhance greatly the effective resolution of the microscope by visualizing energy transfer between donor and acceptor molecules.

In their initial studies, Uster and Pagano used NBD and Sulforhodamine (SRh) as the fluorescent energy donor and acceptor molecules. These probes can be conveniently coupled to proteins or lipids, and they have the necessary spectral overlap for RET. (NBD is excited by blue light and emits green; SRh is excited by green light and emits red.) The investigators modified their microscope with appropriate filters to define three "channels" for observing fluorescence. In the "donor" (NBD) channel, the specimen is excited with blue light, and the resulting green NBD-fluorescence is observed through a narrow "window," which only passes green light. In the "acceptor" (SRh) channel, the specimen is excited with green light and the resulting red fluorescence is observed through filters which only pass red light. In the "transfer" channel, the specimen is excited with the blue light (appropriate for excitation of NBD) but observation of the emitted light is restricted to red wavelengths, characteristic of SRh-fluorescence. Thus any fluorescence seen in the transfer channel is due to energy transfer between NBD and SRh.

Using this new configuration, the investigators carried out initial experiments demonstrating the feasibility of energy transfer microscopy. An example is shown in the photos opposite. Two sets of baby hamster kidney cells were incubated with a fluorescent NBD analog of phosphatidic acid. This lipid intensely labels intracellular membranes, including the endoplasmic reticulum, mitochondria, nuclear envelope, and cytoplasmic lipid droplets. One set of cells (designated "– Acceptor" on figure; photos A and C) received no further treatment. The second set ("+ Acceptor"; photos B and D) had been previously incubated with a sulforhodamine derivative of decylamine. This molecule labels the endoplasmic re-



For use in their studies of lipid transport and distribution in cells, Paul Uster and Richard Pagano at the Department of Embryology are developing resonance energy transfer (RET) microscopy—a new technique which enhances the apparent resolution of the fluorescence microscope. See text, opposite, for explanation of the method and photos A–D, above.

ticulum, mitochondria, and nuclear envelope, but *not* intracellular lipid droplets.

When the doubly labeled cells were examined in the donor channel, only the intracellular lipid droplets were seen (photo B). This is because NBD-fluorescence was quenched by SRh in those cell compartments where the two probes co-localized. When the doubly labeled cells were examined in the transfer channel, SRh fluorescence was visible (photo D). Only those intracellular com-

partments with *both* probes present were fluorescent. This was due to RET between the donor and acceptor molecules which were in close proximity to one another.

In control experiments where cells were labeled with either the NBD-lipid alone (photo C) or the SRh-decylamine alone (not shown), background fluorescence in the transfer channel was minimal. Thus, the investigators conclude that both donor quenching and acceptor enhancement can be seen in living cells using RET microscopy.

Pagano and his colleagues expect to use RET microscopy soon to (1) unequivocally determine whether different lipids, or a lipid and a protein, are in the same intracellular compartment, (2) isolate a single compartment for detailed study if the fluorescent lipid of interest has a multi-compartment distribution, and (3) quantify the kinetics of transbilayer movement and intracellular translocation of lipids *in situ*.

The Sodium Pump. Embedded in the lipid matrix of cell surface membranes are many of the proteins that regulate cell metabolism. Douglas Fambrough is particularly interested in the proteins that form the sodium pump—the principal mechanism used by excitable nerve and muscle cells in maintaining essential transmembrane ionic imbalances.

Several years ago, having developed a cell line that secretes a monoclonal antibody to the sodium pump, Fambrough initiated quantitative studies on the number and distribution of sodium pump molecules in neurons and muscle fibers. His preliminary studies suggested several new ideas about the sodium pump and its regulation. For example, he found that different levels of abundance of the sodium pump in different muscle fibers of the same muscle correlated exactly with the variety of muscle fiber types defined by classical (but not well understood) histochemical techniques. (These differences had not been appreciated from earlier studies on the biochemistry of whole muscles.) Thus, fibers used for long-term steady maintenance of muscle tone require a modest abundance of sodium pumps, while fibers recruited for short-term, quick bursts require high levels.

This finding suggested, in turn, that there might be a rapid, up-and-down regulation of the sodium pump in muscle fibers to set abundance at appropriate levels for muscle function. Fambrough and his colleagues followed up this idea during the report year with an extensive study of the modulation of sodium pump abundance in skeletal muscle fibers grown in tissue culture. They found that, as conditions permit faster influx of sodium ions, muscle fibers show a marked increase in the rate of biosynthesis of sodium pump molecules. As the system approaches steady-state, the rate of biosynthesis returns to normal, although with a continuing high influx of sodium molecules the muscle fibers maintain an elevated level of

sodium pump abundance. This maintenance is accomplished by a decrease in the rate of degradation of sodium pump molecules. Once enhanced sodium influx to the muscle fibers is stopped, sodium pump levels rapidly return to normal.

In his studies on the origin, transport, and assembly of the sodium pump, Fambrough is laying the groundwork for a more general study of how sodium pump structure is correlated with function and regulation. In this effort, he and his colleagues are employing many techniques of genetic engineering. For example, they are attempting to clone the DNAs encoding parts of not only the sodium pump but also the calcium pump, which is a protein of skeletal muscle fiber involved in muscle contraction. The sodium and calcium pumps are homologous in structure and function, yet they differ in ion selectivity and mechanisms of regulation. Fambrough *et al.* hope that comparisons will yield information about what structural differences are essential for differences in function and bioregulation. Fambrough intends to continue these studies at the Johns Hopkins University Biology Department, which he joined on July 1, 1985.

Membrane Traffic: Receptors. The cell surface membrane is intimately related to a complex set of at least ten different internal organelles. Constituents are exchanged among these organelles and the cell surface by a traffic of membrane vesicles. Martin Snider, a staff associate at the Department of Embryology, is interested in the nature of this traffic. Specifically, he is interested in the movement of cell surface receptors. Receptors are proteins that selectively bind extracellular molecules needed by the cell (for example, hormones and nutrients). Once bound, a receptor and its passenger move into the cell in membrane vesicles. The receptor then releases its bound molecule at a target site and rapidly returns to the membrane surface.

Snider and his colleagues have developed a novel approach to track receptors in cells. The technique uses special enzymes—"marker enzymes"—that are found in particular intracellular compartments. Snider modifies a receptor on the cell surface so that it can be acted on by a particular marker enzyme molecule. He then allows the receptor to bind to an extracellular substance, move inside, deposit its passenger, and return to the surface. He then examines the receptor to see if it has been acted on by the marker enzyme. If it has, he knows it has passed through the compartment that contains that enzyme.

Snider and his co-workers have used this approach to study the movement of transferrin receptor through the Golgi complex. (Mammalian cells use this receptor to get iron from the circulation.) Last year, they showed that the transferrin receptor moves through a distal part of the Golgi. (This is the region closest to the cell surface.) This year, they have shown that the

receptor also enters a proximal Golgi region, although it does so more slowly. In addition, a large number of other cell membrane proteins also pass through this region. The Golgi has been thought to function primarily in the synthesis and secretion of proteins from the cell. Snider's results suggest that the outward membrane traffic required for secretion and the inward membrane traffic of receptors and other proteins actually intersect in this organelle.

Regulation of Nutrient Uptake in Algae. When a cell is deprived of a needed nutrient, the profile of its membrane changes. At the Department of Plant Biology, Arthur Grossman and postdoctoral fellow Laura Green have recently begun to look at some of these changes in the cell surface membrane proteins which accompany sulfate deprivation in the cyanobacterium *Anacystis nidulans*. Their work is part of an effort to better understand the means by which organisms acommodate stresses in their environments.

Grossman and Green found that membranes of algal cells transferred to a sulfur-free medium dramatically increase their capacity to take up sulfur. Preliminary evidence suggests that this increase may reflect synthesis and assembly into the membrane of an inorganic sulfate transport system present in low levels in sulfate-sufficient cells. In the future, Grossman and Green hope to identify specific membrane protein(s) associated with this event and to examine ways in which synthesis is regulated.

Photosynthesis: Structure, Function, and Response to Stress

> The center of interest for the photosynthetic process is the chloroplast. The chloroplasts are as important to an understanding of this process . . . as the chromosomes are for heredity.
>
> H. A. Spoehr
> Chairman, Division of Plant Biology
> 1938

A plant cell contains from one to forty chloroplasts. Within each chloroplast is an intricate array of membrane-bound organelles where the complex process of photosynthesis takes place. These organelles are called thylakoids. Each thylakoid contains two pigment-protein complexes called photosystems. Both photosystem I and photosystem II contain light-gathering "antenna" complexes of chlorophyll *a*, carotenoids, and other pigments, which capture light from a broad range of the spectrum. (Photosystem I traps light in long, red wavelengths; photosystem II traps light in shorter, redder wavelengths.) The trapped energy in each system passes to a reaction center complex (also in the thylakoid), which contains a special chlorophyll *a* molecule that starts the next step of the photosynthetic process.

At the Department of Plant Biology, interest in photosynthesis remains as strong as ever. Staff member Jeanette Brown concentrates on the structural arrangement of pigments and proteins in the thylakoid. Meanwhile, David Fork, Joseph Berry, Olle Björkman, and their colleagues investigate how the photosynthetic apparati respond to environmental stress. Evidence gathered over the years suggests that primary damage to the light-gathering system in stressed plants occurs within photosystem II, but knowledge of the exact site, as well as the molecular mechanisms involved, is still lacking. Filling in this gap in knowledge is a major goal at the Department.

Pigment Structure in the Thylakoid. For many years, Jeanette Brown has studied the functional arrangement of the pigments involved in photosynthesis. She and her colleagues (which include this year Lise Caron, a Carnegie–del Duca fellow, and Grazyna Bialek-Bylka, a postdoctoral fellow from Poland) have recently developed procedures for isolating three major pigment-protein complexes from thylakoid membranes without altering their molecular configurations. By means of extensive absorption and fluorescence spectroscopic studies, they have characterized the nature of chlorophyll *a* bound to the different proteins of each.

Last year, they began using a newly acquired high-performance liquid chromatography apparatus to separate various other chlorophylls and carotenoids. The apparatus enables them to measure pigments in amounts as low as a few millionths of a gram. So far they find that β-carotene is bound only to the reaction center complexes, whereas the other carotenes and xanthophylls are bound to the antenna complexes. Eventually, they hope to formulate a molecular model for how all the pigments are functionally arranged.

Photoinhibition. Light is the driving force of photosynthesis. As its intensity increases, so does the rate of photosynthesis. Under certain conditions, however, light intensity may exceed the capacity with which it can be used. Too much light may damage the photosynthetic system, causing what is called photoinhibition. Scientists at the Department of Plant Biology have previously shown that photoinhibition occurs when plants grown in weak light are suddenly exposed to bright light. Photoinhibition can also occur when plants native to sunny locations are exposed to such environmental stresses as low temperature, drought, and high salinity.

Olle Björkman is especially interested in the interactive effects of light with different environmental stress factors. This is a difficult area to study because plant cells possess repair mechanisms that may permit partial or full recovery from photoinhibition once a stress is removed. Hence, Björkman notes, it seems probable that

the recovery process may proceed concurrently with the inhibition process; the observed photoinhibition may thus reflect the balance between these two processes. Stress factors could act either by accelerating the photoinhibitory process or by suppressing the recovery process.

During the report year, Björkman and Barbara Demmig (a postdoctoral fellow from Würzburg, Germany) have investigated the kinetics of the photoinhibition and recovery processes in plants grown under different light regimes. They find that when sun-grown leaves held at low light for an hour or more are suddenly exposed to bright light, they show rapid and pronounced reduction in fluorescence yield, a measurement made at −196°C. If the leaf is returned to shade before the measurement is made, no evidence of photoinhibition is found. When, however, shade-grown leaves are exposed to bright light, irreversible photoinhibition-related changes in fluorescence occur. Björkman suggests that the reversible reduction in fluorescence yield in sun-grown leaves may be indicative of the operation in these leaves of a protective mechanism that in shade leaves is poorly developed. He and his colleagues are currently exploring this possibility.

Björkman, Joseph Berry, and Dennis Greer (a postdoctoral fellow from New Zealand) completed a study this year on the temperature dependence of recovery from photoinhibition. This group found that in light-damaged bean cells no measurable recovery occurred below 10°C. But above 10°, recovery increased strongly with temperature until it reached a maximum at about 30°C. Strongly promoted by weak light, the recovery process was blocked by applying to leaves an inhibitor known to prevent chloroplast-encoded protein synthesis. It appears from these results, says Björkman, that recovery from photoinhibition depends on the operation of some kind of light-dependent repair mechanism. Björkman and postdoctoral fellow Max Seyfried are currently investigating this possibility.

Björkman has also continued his studies with Australian mangroves. The sun-exposed leaves of these plants, which live in full-strength sea water, can suffer appreciable photoinhibitory damage. Last year, Björkman suggested that physiological "drought" associated with the high salinity of the water predisposes the mangroves to photoinhibition, just as desiccation predisposes desert plants to photoinhibition. Experiments conducted during the report year confirmed this hypothesis. But, contrary to expectation, Björkman and Demmig found no evidence that high salinity suppresses the recovery process. Thus, it appears that high salinity (or the resulting water stress) acts upon the inhibition process itself.

Heat Stress. David Fork, like Björkman, studies the effects of stress on photosynthetic mechanisms. His studies, however, are

primarily at the biophysical level, and are directed at understanding how the photosynthetic apparatus—particularly the thylakoid membranes—react to heat stress. In this work, he and postdoctoral fellows Prasanna Mohanty and Satoshi Hoshina have developed a sensitive probe, called delayed light emission, to detect early photosynthetic heat damage.

Delayed light is the extremely faint glow emitted by all photosynthetic plants after they have been illuminated. Fork and his colleagues found that slow heating of plant samples until they were irreversibly damaged caused a gradual increase in delayed light. The luminescence reached a maximum and then declined to zero. The maximum for each plant was characteristic of the species as a whole.

The group found similar declines in delayed light when measuring the effects of high temperature on various photosynthetic reactions that require the physical integrity of thylakoid membranes. About ten years ago, former Plant Biology fellows Ulrich Schreiber and Paul Armond suggested that heat treatment led to a physical dissociation of the thylakoid membrane's photosystem II chlorophyll-protein complexes (*Year Book 76*, p. 341).

This idea was confirmed and extended by electron microscopic measurements done in the University of London laboratory of former fellow Patrick Williams. Williams found that mild heating of bean cells caused the dissociation of the chlorophyll *a*/*b* light-harvesting pigment protein embedded within the thylakoid membrane. Continued heating above this temperature led to phase separation of a particular class of lipids that do not form the sort of bilayers usually assumed to exist in biological membranes. After heating, these lipids were seen to have rearranged themselves in repeated arrays of cylindrical structures. Williams suggested that these lipids may play an important role in holding the light-harvesting pigment proteins to the thylakoid membrane and that their exclusion from the membrane during heat treatment could underlie the resulting damage.

In further study of this phenomenon this year, Williams, Fork, and Arindam Sen from the Roswell Park Memorial Institute in Buffalo saw in heated chloroplasts from pea that heat-induced disorganization of thylakoid membranes gave rise to a delayed light emission response, as well as several other changes. Fork notes that all of the observed changes may be related to the appearance of the non-bilayer lipid structures.

From the results of these and other experiments, Fork believes that delayed light emission is a valuable tool in the detection of heat-induced changes occurring in chloroplast organization and function. He notes that the technique may even some day serve as a useful method of screening plants for tolerances to high temperature.

Serendipity and RuBisCO

Every once in a while experiments lead to unexpected discoveries.

Joseph Berry
Department of Plant Biology
July 1985

Plants have developed ingenious ways to adapt to environmental extremes. About a decade ago, Joseph Berry discovered that algal cells deprived of carbon dioxide could manufacture a transport system that allowed them to take advantage of bicarbonate (HCO_3^-). Once CO_2 levels returned to normal, the bicarbonate system vanished. This year, Berry and his colleagues unexpectedly discovered yet another adaptive mechanism—one that operates not in emergency, but under normal conditions.

The discovery of this system came as a surprise. Berry had originally set up a series of experiments designed to investigate differences in the activity of a major photosynthetic enzyme among plants of different lineages. He and his colleagues had earlier found that this enzyme, called RuBisCO (ribulose-1,5-bisphosphate carboxylase/oxygenase), is able to function with varying efficiency in plants of different species—presumably because the enzymes have slightly different amino acid sequences. In the course of their experiments last year, Berry and postdoctoral fellow Jeffrey Seemann uncovered unexpected variation in the activity of RuBisCO in a single species, the common bean.

When first detected, this variation in bean was, according to Berry, a "nuisance." With further study, however, he and Seemann found that the variation was quite interesting. It appeared, in fact, to be a manifestation of the elaborate means by which the leaves of some plants (such as beans) regulate the activity of their RuBisCO. In the dark, when the leaf cannot conduct photosynthesis, some sort of inhibitor blocks RuBisCO's activity by 90%. In the bright sun of midday, however, when photosynthesis is at its peak, the inhibitor is not present and enzyme activity is high. Mechanisms that synthesize or degrade the inhibitor thus regulate its concentration in coordination with available light. This explains why the activity of RuBisCO originally appeared to be different from plant to plant; Berry and Seemann had run some of the experiments too early in the morning.

Berry notes that similar regulatory processes are known to exist in most of the major metabolic pathways. The mechanisms used to achieve this control are diverse, but they all appear to function as "valves." As such, they serve to maintain some degree of internal balance despite a constantly changing external environment. Two features of the system newly discovered in bean, however, are

unique. First, the system seems to occur in some species, while it is lacking in others. Second, it operates by the formation of a specific "poison"; most regulatory mechanisms, in contrast, operate by the modification of a particular enzyme.

Seemann and Berry have not yet identified the inhibiting substance in bean responsible for RuBisCO regulation. But they know that it exists within the chloroplast, that it is a phosphorylated compound that can be degraded enzymatically, and that it works by binding to RuBisCO in place of the normal substrate. They plan to do chemical studies as soon as they have isolated sizable quantities. Meanwhile, they are continuing their efforts to find differences in the efficiency of RuBisCO among species. If superior variants can be identified, it is possible, writes Berry, that these variants could be used to obtain improved rates of photosynthesis from the same quantity of total protein.

Light and Plant Growth

> Before the name "Very Low Fluence Response" was even coined, researchers in the Briggs laboratory were characterizing phytochrome-mediated responses of plants requiring very low levels of red light. . . .
>
> James Shinkle
> Department of Plant Biology
> July 1985

Phytochrome-Mediated Responses. Plants require light to germinate, flower, and grow. The pigments regulating these activities respond to various wavelengths, or colors, of light. Some respond to blue, some to red, and some, like chlorophyll, respond to both blue and red. One interesting pigment—phytochrome—contains two forms; one responds to red light, the other responds to far red light. Phytochrome regulates many nonphotosynthetic chemical changes in plants, such as seed germination, flowering events, and stem elongation.

In 1977, members of Winslow Briggs's lab at the Department of Plant Biology noticed that gravitropism (bending downward) in corn roots was stimulated by very low levels of red light—levels equivalent to from one to ten firefly flashes. Apparently only a very small portion of the total phytochrome in the plant was needed to absorb enough red light to cause a response. Such low-level phytochrome-mediated responses (which in 1980 were officially named "very low fluence responses," or VLFRs) have since become a major focus of the Briggs lab.

Winslow Briggs spent the current report year in Freiburg, West Germany, on sabbatical leave, but members of his Plant Biology group continued their photomorphological studies. Predoctoral fel-

low James Shinkle, for example, continued an effort to characterize the physiological conditions required for the expression of the VLFR in dark-grown oat and corn seedlings. These events include the inhibition of stem elongation and the stimulation of leaf growth. Last year, Shinkle found that the hormone auxin had to be present in order for the VLFR response to occur. This year, he found that the VLFR response was specifically tied both to the auxin-promoted decrease in extracellular pH (which caused the response) and to high concentrations of potassium ions in the external medium (which eliminated the response). He found further that the actions of both extracellular pH and high potassium are rapid. This suggested to him that the effects are occurring early in the phytochrome signal transduction chain and could be of considerable value in elucidating the nature of this important series of events.

Blue Light. The way that plants respond to red light is yet poorly understood. Even less understood is how plants respond to blue light. This year, postdoctoral fellow Moritoshi Iino, in collaboration with Eduardo Zeiger of Stanford, discovered a blue light response in the outside (epidermal) leaf cells of the common spiderwort (*Commelina communis*). They discovered that the opening of the leaf's stomata (gas-exchange valves) was directly proportional to the time of blue light irradiation, with a 100-second irradiation saturating the response.

Iino's discovery of a blue light response in the plant epidermis is significant because the stomata provides an amenable system for study: stomatal opening depends on light received by single cells (guard cells). The only other favorable option for the study of blue light responses—the bending of plants toward light (phototropism)—occurs in organs containing many cells, each one of which is subject to differing light intensities. Analysis of the resulting data is thus quite difficult.

Despite this, Tobias Baskin, a graduate student working in Briggs's lab, has made progress in understanding how blue light stimulates phototropism. He finds that seedlings of pea, a dicot, have phototropic responses to pulses of blue light that are nearly identical to those of maize, a monocot. It appears, therefore, that a common mechanism for phototropism may be widely shared in the plant kingdom.

Ecology: Physiological Responses

My approach emphasizes the comparative analysis of closely related species which share a common evolutionary background but differ in characters of interest. It is an approach powerfully developed by

Clausen, Keck, and Hiesey, working at Carnegie in the first half of this century.

Christopher Field
Department of Plant Biology
July 1985

Habitat Breadth in a Tropical Rain Forest. Many plant species in nature survive in a wide variety of habitat types. Others are strictly limited to narrowly defined environments. It is an accepted, but yet unproven, hypothesis that the broad-ranging species in any given habitat are not as finely tuned to their environments as are species that live in narrow ranges. This hypothesis is sometimes stated with the adage that "a jack of all trades is the master of none."

The newest staff member of the Department of Plant Biology, Christopher Field, this year examined some physiological aspects of habitat breadth in closely related species of the tropical genus *Piper.* Included in this genus is the most economically important of all spice plants—*Piper nigrum*, or black pepper.

At his primary field site (in the Los Tuxtlas biological preserve of the National Autonomous University of Mexico), Field found eight *Piper* species, each of which live in only a single type of light habitat. He found two other *Piper* species that germinate and begin life in exposed clearing but persist as the forest re-establishes. Through their lives, individuals of these two species (the "generalists") thus encounter nearly the entire range of tropical forest light habitats.

So far, Field has concentrated on documenting physiological differences among the *Piper* species. In preliminary experiments, he has found, surprisingly, that the generalist species and those species that live only in sun are not dramatically different in their ability to adjust photosynthetic characteristics in response to

Christopher Field measures light availability for tropical pepper plants (*Piper* species) in Department of Plant Biology greenhouse.

light during growth. However, the species show different modes of acclimation. The generalists vary their canopy architecture and leaf structure in response to habitat variation, while the sun species respond by changing their photosynthetic apparati.

Field's work with *Piper* as a model system in understanding habitat preference and breadth is one of only a few studies designed to probe in detail the physiological ecology of lowland tropical forests. Tropical environments are among the Earth's most diverse, threatened, and biologically unknown ecosystems. His results thus promise to be of interest not only to his fellow ecologists but also to forest managers concerned with tropical ecosystem reestablishment.

Resource Acquisition and Allocation. Resources in tropical forests are often limiting. Nearly all the nitrogen, for example, is held within the living biomass; little is found in the soil. Light is also in short supply for plants living under the forest canopy. How, then, do plants solve the problem of getting enough nutrients and energy? How do they best allocate available resources to the leaves, roots, and reproductive organs?

Problems of resource acquisition and allocation are at the heart of plant productivity studies recently initiated by Olle Björkman and his collaborator Harold Mooney of Stanford University. Plant productivity studies have been hampered by a lack of integrated information on how allocation patterns are affected by the environment and how they interact with photosynthetic activity and nitrogen acquisition processes over the lifetime of a plant. Björkman and Mooney are investigating some of these relationships using wild and cultivated varieties of radish as a model system.

Wild radishes grow much faster and attain a larger size than do cultivated radish plants. In studies comparing one wild type and one cultivated genotype, Björkman and Mooney find that both species have the same leaf photosynthetic characteristics and that both acquire nitrogen with equal efficiency. They conclude, therefore, that the enormous difference in growth rate must be attributed to differences in resource allocation: wild radishes invest most of their energy and nutrients (up to 90%) into new leaf and root growth, while cultivated radishes allocate over 60% of their resources to storage.

The extensive data base that Björkman and Mooney obtained for the wild type of photosynthetic characteristics, nitrogen uptake rates, and the response of these parameters and of the allocation pattern to different environmental conditions is now being used for the construction of a dynamic growth model. The two investigators hope that this model will provide a framework for examination of the implications of various growth strategies in different natural environments.

Oxygen Evolution in the Biosphere

> For several years now, [we] have discussed the possibility for collaborative research that would draw upon the different strengths of the two programs. This year represents an important breakthrough with actual experiments in progress.
>
> Joseph Berry, Department of Plant Biology
> Marilyn Estep, Geophysical Laboratory
> 1985

It is well known that purely geological processes, such as volcanism and plate tectonics, play important roles in the shaping of our planet over time. Biological processes of photosynthesis and respiration (the two main energy-yielding systems in living organisms) also contribute to the evolution of the Earth. Without photosynthesis, for example, life on the primitive Earth would have ceased. Not only would primitive heterotrophs (nutrient users) have depleted their environment of organic compounds, but also their metabolism, which would have been fermentive in the absence of oxygen, would have increased the level of carbon dioxide to a point where even fermentation would not have worked. It was only with the increased addition to the atmosphere of oxygen—the byproduct of photosynthesis—that heterotrophs were able to develop biochemical pathways of respiration, an oxygen-using process that allowed them to extract nutrients from the environment with much greater efficiency.

The biochemical processes of photosynthesis and respiration have not changed much over billions of years of evolution. It is thus possible to examine the metabolisms of now-living organisms for information about past events. This is the rationale behind the work of Marilyn Estep, a biogeochemist of the Institution's Geophysical Laboratory. Estep and fellow staff member Thomas Hoering use stable isotopes of oxygen, nitrogen, hydrogen, and sulfur as natural tracers in understanding biochemical pathways of metabolism. Although interest in the use of stable isotopes in plant physiology and ecology has been increasing, biologists have not yet obtained for this work the instrumentation or experimental tradition that exist in the geological sciences. The collaboration begun this year between Estep and Hoering and Joseph Berry of the Department of Plant Biology, with visiting investigator Robert Guy from the University of Calgary, is a first attempt to bridge this gap.

In March 1985, with a collection of vacuum pumps, stopcocks, glass tubing, and clamps, Estep and Hoering assembled at the Department of Plant Biology a sample preparation line modeled after one they had built earlier at the Geophysical Laboratory.

They designed the instrumentation so that experiments could be conducted in Stanford but analyses run in Washington using the Geophysical Laboratory's mass spectrometers.

A long-term goal of the group is to better understand the biogeochemical cycling of oxygen in the biosphere. Specifically, the scientists hope to find a quantitative explanation for the observation, made many years ago, that the oxygen of the atmosphere has relatively more of the heavy isotope of oxygen, ^{18}O, than does water of the oceans. They hope also that the results will provide insights into mechanisms of biochemical reactions, and provide, as well, new approaches for the study of respiratory processes in plants.

The initial experiments were designed by Berry, Guy, and Estep (who spent several weeks at the Department) to measure how the stable isotopes of oxygen are fractionated, or broken down, in photosynthesizing organisms. The group compared the isotopic composition of oxygen gas produced by spinach chloroplasts with the oxygen isotopic composition of the water in which the chloroplasts were suspended. They found that the isotopic composition of the oxygen entering the atmosphere is essentially identical to that of the water. These results confirmed previous speculations—drawn from inconclusive experiments on intact organisms—that very little fractionation occurs in photosynthetic (oxygen evolution) reactions. The older observations that atmospheric oxygen is enriched with ^{18}O must therefore indicate that atmospheric processes that consume oxygen preferentially use ^{16}O, leaving the heavier isotope behind. This possibility has been examined in preliminary studies using yeast.

Other experiments, now in progress, are designed to measure how photorespiration affects oxygen isotopic fractionation. Photorespiration is a companion process to photosynthesis. Like normal respiration in both plants and animals, it uses oxygen and produces carbon dioxide, but, unlike the normal mechanism of respiration, it results in no energy gain. In fact, it appears to be energy wasteful. The process may use up to 30% of the oxygen produced by photosynthesis. If it discriminates against the heavier isotope of oxygen (as occurs in mechanisms of respiration in microorganisms), then such discrimination could have a large effect on the composition of the net oxygen produced by plants worldwide.

The Human Embryo Collection

During the report year, Department of Embryology research associate Ronan O'Rahilly and colleagues Fabiola Müller, Grover Hutchins, and G. William Moore studied aspects of the nervous system, ectodermal ring, and respiratory and digestive systems of developing human embryos. In their work, they used the collection of

human embryos gathered in the first part of the century by scientists of the Department of Embryology. The collection is now housed at the Carnegie Laboratories of Embryology in Davis, California.

Highlights of the year include the development of a computerized bubble-sort algorithm in ranking 165 staged embryos of the first five weeks in ascending order as some 100 features of the developing brain appear. The vast majority of features appear during either one or two stages (about two or three days). These results, O'Rahilly writes, confirm the Carnegie system of embryonic staging.

O'Rahilly and Müller compared the greatest length and the crown-rump length in 43 staged human embryos. They found that the differences between the two lengths are small up to seven weeks and basically nonexistent after that. Since the greatest length is simpler to measure than the crown-rump length, and because its measurement is practicable both earlier and later than crown-rump measurements, O'Rahilly and Müller recommend that it be used instead. They point out that George Streeter, a former director of the Department of Embryology, had made this substitution years ago.

By means of graphic reconstructions of the general surface anatomy of early human embryos, O'Rahilly and Müller studied an important but previously neglected feature—the ectodermal ring—in seven embryos of stages 10–16 (three to five weeks). In studying the digestive and respiratory systems, they have shown to be incorrect some commonly held views such as the supposed candorostral separation of trachea from esophagus. In such work, they have shown the applicability of valid embryological data to the interpretation of congenital anomalies.

Inquiries concerning the human and comparative collections, as well as requests for permission for publication, should be addressed to Professor Ronan O'Rahilly, Carnegie Laboratories of Embryology, California Primate Research Center, Davis, California 95616.

The Physical Sciences

Spaceborne research—its early achievement and its remarkable promise for the near future—increasingly colors research in the earth and planetary sciences and in astronomy. Earth-orbiting satellites are providing for the first time a well-integrated and worldwide mapping of the Earth's physiographic features as well as its

gravity and magnetic fields. Lunar and planetary explorations have led us to cease thinking of the Earth as a unique object, and recent discoveries of orbiting material about other stars suggest that, before long, the solar system too will be regarded as one of many. Astronomy from space is becoming a growing reality.

At the same time, vast changes are occurring in that much larger part of research in the physical sciences that is still Earth-bound. Advancing technology for portable seismic instruments, for example, is raising the possibility of studying specific regions of the inner Earth in detail. In astronomy, an electronic revolution is fast increasing the dimensions of the observable Universe, and there is widespread recognition that in order to exploit fully the promise of spaceborne observation, a new generation of greater, ground-based telescopes is needed. The unprecedented capability for numerical simulations, or models, inherent in modern, fast computers, for example, has added a new dimension to the process of discovery.

But though the powers of the new research tools are indeed remarkable, their role remains to reinforce the most critical values of the past, not to supersede them. A significant discovery may seem a dramatic event—perhaps the acquiring of a final missing piece which allows a major new synthesis across many subdisciplines. But even such a happening usually represents an outcome of many earlier steps by many investigators engaged in the gaining and interpreting of new evidence. Driving the process remain knowledge, perception, judgment, and originality in the mind of the researcher.

Together then, the two points represent a continuing force in science—the necessity on the one hand to pursue aggressively the newest opportunities of the moment, while at the same time building upon the values and achievements of the past. It is an outlook reflected in the May resolutions of the Institution's trustees, to bring to a single site the programs of the Geophysical Laboratory and the Department of Terrestrial Magnetism (DTM) and to proceed toward the building of a major (8-meter) telescope at Las Campanas.

Structure, Rotation, and the Question of the Interaction of Galaxies

Inherent in Hubble's original scheme was the belief that a galaxy evolved in splendid isolation, living out its life within the Hubble class to which it was born. In an amazing turnabout, astronomers now understand that a galaxy is a continuously evolving structure, which will acquire stars or lose stars through gravitational interactions, will acquire gas or lose gas through infall or galactic winds, will be actively forming stars or be quiescent depending on its most recent history, and will look like an elliptical or a spiral

depending upon the eyes of the beholder and
the limiting magnitude of the telescope exposure.

Vera C. Rubin
Department of Terrestrial Magnetism
July 1985

Until lately, almost any discussion about how galaxies formed began with the idea that every galaxy now seen (with a few exceptions), including our own, was formed in a collapsing cloud of gas and dust. Where star formation occurred late in the collapse—after most of the gas and dust had assumed the shape of a rotating disk—we now see a symmetric, spiral galaxy. But where the material available for star formation was used up early in the collapse, we see an elliptical galaxy, characterized by a lack of ordered rotation and active star formation. This picture, developed in the early 1960s, until recently seemed adequate to explain most of the features observable in galaxies.

The limitations of this picture became apparent in the last few years—a product of the growing power of electronic detectors and the increasing use of computer simulation. That galaxies might sometimes interact, altering one another's structure, was already evident in the various distorted galaxies displayed in the 1966 *Atlas of Peculiar Galaxies*, by Carnegie astronomer Halton Arp. During the 1970s, computations by Alar Toomre at MIT showed that encounters and interactions between galaxies are probably more frequent than had been supposed. Toomre and others sought and found observational evidence—telltale features indicating that galaxy interactions or mergers were now taking place or had occurred relatively recently. The same telltale features could be reproduced in computer simulations of interacting galaxies. The emerging concept—that many of the galaxies we now see on the sky are not primordial but are products of interactions and collisions of earlier galaxies—is now among the most vibrant in astronomy today.

The Polar-Ring Galaxies. Perhaps the most remarkable insights into mergers have come from the polar-ring galaxies, of which about two dozen are now known. Each consists of an S0 disk galaxy seen edge-on, along with a fainter disk of material in orbit at right angles to the primary S0. On photographs, a polar-ring galaxy looks like a cigar encircled by a ring, but the true configuration—two perpendicular disks—was confirmed several years ago from measurements of rotation. Since the disks of the cigar and ring have separate axes of rotation, they must have formed in separate events, and the ring galaxies now seen must be products of past mergers. Star formation is typically seen in the ring, which is made of debris from the lesser galaxy in the merger.

This year, Mount Wilson and Las Campanas Observatories staff members Paul Schechter and Jerome Kristian, with Jacqueline van Gorkom of the National Radio Astronomy Observatory, obtained radio observations of three polar-ring galaxies. Working at the Very Large Array in New Mexico, they observed the strong emissions of neutral hydrogen at wavelength 21 centimeters.

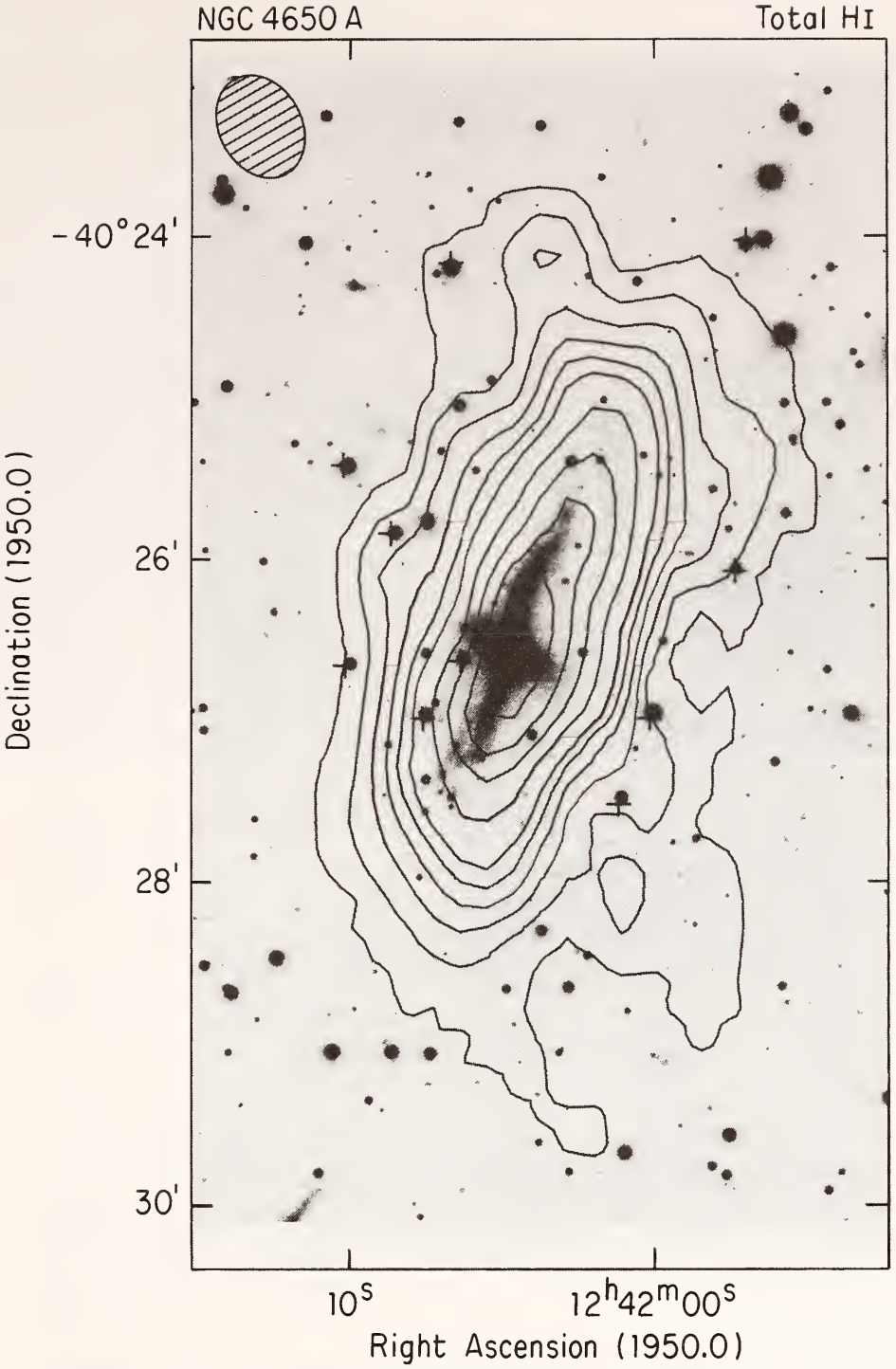
The presence of gas is a prerequisite for star formation. In one case, A0136-0801, the investigators found that the hydrogen gas is more or less coextensive with the starlight from the polar ring. As in two other familiar ring galaxies (II Zwicky 73 and UGC 7576), this condition indicates that the ring has had ample time to form stars.

The situation is very different in the other two galaxies. In NGC 4650A, most of the hydrogen appears to have settled into the ring, but there is still hydrogen distributed nonsymmetrically at the outskirts; star formation is seen only in a narrow part of the ring. Evidently, there has not been enough time for the gas to settle into the ring and complete its star formation. In MCG 5-7-1, the hydrogen is distributed even more nonsymmetrically, and the gas extends far beyond the visible image of the galaxy. Enough hydrogen has settled, however, for the narrow ring of stars to have formed. This galaxy is distinctive in that it is surrounded by stellar debris—another indication of its relative youth and of its origin as the product of the merger of two galaxies.

In MCG 5-7-1, the planes of the ring and the dominant S0 are not exactly perpendicular to one another. This condition violates the expected behavior of gas in an elliptical gravitational field. Schechter *et al.* plan to make further radio observations at high resolution in hope of resolving this puzzle.

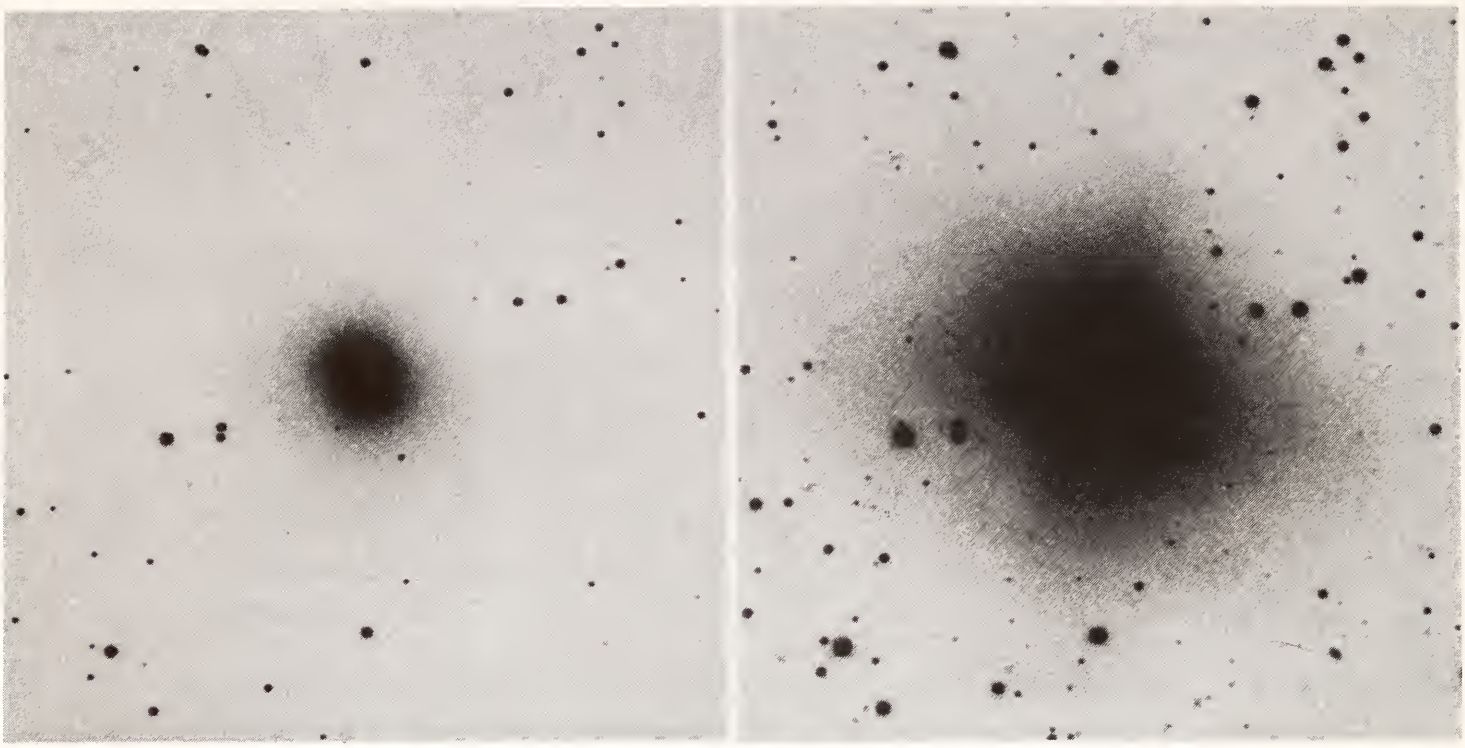
Fine Structure in Ellipticals. In a landmark paper published in 1930, Edwin Hubble analyzed the distribution of luminosity in fifteen elliptical galaxies and derived the simple analytical expression for their brightness profiles that now bears his name. Later astronomers found appealing the simplicity and universality of Hubble profiles, and accepted easily the seeming smoothness of the light distribution in ellipticals. But in the late 1970s, looking at otherwise normal-appearing ellipticals, astronomers began to find various fine structures—shells, ripples, and plumes, irregular features made of old stars, inclined gas disks, and lanes of dust. From computer simulations, it seemed likely that some of these structures were relics of recent collisions and mergers with other galaxies.

DTM astronomers François Schweizer and W. Kent Ford have begun a program to find, measure, and catalog such fine structures by applying digital filtering techniques to photographic images of ellipticals. They have discovered a new, interesting type of fine structure—crossed streamers of luminous material,



Contours of constant neutral hydrogen surface density, superposed on a photograph of the polar-ring galaxy NGC 4650A. Polar-ring galaxies have been shown to be products of recent galaxy interactions or mergers. The hydrogen data are from radio observations by Paul Schechter and Jerome Kristian of the Observatories, and Jacqueline van Gorkum of the National Radio Astronomy Observatory, obtained at the Very Large Array in New Mexico. It can be seen that most of the hydrogen has settled into a disk shape in the plane of the ring, though there is still hydrogen distributed nonsymmetrically at the outskirts. (Photo, courtesy of Ken-ichi Wakamatsu, Gifu University, Japan.)

seen in the relatively isolated Southern elliptical IC 3370. The streamers seem to be related geometrically to box-shaped patterns of brightness inside the galaxy. While attending a meeting at Toulouse in late 1984, Schweizer met Christopher Dupraz of the



DTM astronomers François Schweizer and W. Kent Ford have found a new, interesting fine structure in the outer regions of the elliptical galaxy IC 3370. The view at left (10-minute exposure) shows the galaxy's apparently normal inner structure. The view at right (90-minute exposure) shows unusual "crossed streamers" in the outer regions. Schweizer and Ford believe that the streamers are the stellar debris of a small disk galaxy that recently fell into the elliptical and was disrupted during the subsequent merging. The photographs were taken with the 4-meter telescope at Cerro Tololo, Chile.

University of Paris and learned of the latter's numerical simulations of the infall of a small spiral galaxy into a large elliptical. Dupraz, it turned out, had found strikingly similar crossed structures. The episode was a remarkable example of how observational and theoretical work can be complementary. Like the ripples and tails seen previously, the crossed features are signatures of a past merger.

Meanwhile, Schweizer, Ford, and Patrick Seitzer of Kitt Peak National Observatory have initiated a survey of fine structure in Northern elliptical and S0 galaxies. They are employing state-of-the-art CCD detectors, which are much superior to photographic plates in signal-to-noise ratios and therefore in their ability to detect weak structures. The investigators have imaged some sixty galaxies to date at the 1-meter telescope at Kitt Peak and the 5-meter at Palomar. They are finding fine structures in the S0's similar to those in the ellipticals. They note that both the E and S0 galaxies lack gas and young stars, and they believe that this depletion may have occurred in past merger events—a product of the super-efficient conversion of gas into stars during mergers, along with the subsequent hot galactic winds that push away most of the remaining gas.

Computer Simulations of Galaxy Interactions. DTM postdoctoral fellow Kirk Borne has analyzed the interactions between galaxies, generally ellipticals, that exist in pairs. His numerical models are constrained to fit measurements of light distributions and motions inside each galaxy—data that he has obtained in observations at Kitt Peak during the last four years.

In the case of the galaxy pair NGC 4782 and 4783, Borne's simulation shows that the two galaxies have approached one another on an unbound trajectory, that they are just past closest approach, and that they are undergoing a tidal shock. That shock of interaction, he notes, momentarily accelerates the stars, causing a transient peak in the range of their velocities. (This momentarily high velocity dispersion led to earlier, falsely high determinations of galaxy mass—a result that seemed to indicate the possible presence of a massive invisible halo.) Borne derives normal values of mass and mass-to-luminosity ratio from the simulation, and he concludes that distortions in the galaxies—unusual motions and nonsymmetric light distributions—are evidence that energy is being drawn from the orbit of the pair and transferred into the motions of the individual stars. The orbital decay and merger of the two galaxies is inevitable.

Borne's similar results with other pairs of ellipticals further illustrate the gravitational origin of the observed distortions, and add evidence strengthening the idea that mergers have strongly influenced the population of galaxies now seen.

Environmental Effects on Spirals? Seeking evidence that galaxies in densely populated regions are disturbed relatively frequently in their lifetimes, Vera Rubin and Kent Ford, with former DTM postdoctoral fellow David Burstein (Arizona State University) recently analyzed rotation curves of many spiral galaxies situated in clusters. They found significant differences between the rotational characteristics of cluster galaxies and those of isolated, noncluster galaxies studied earlier.

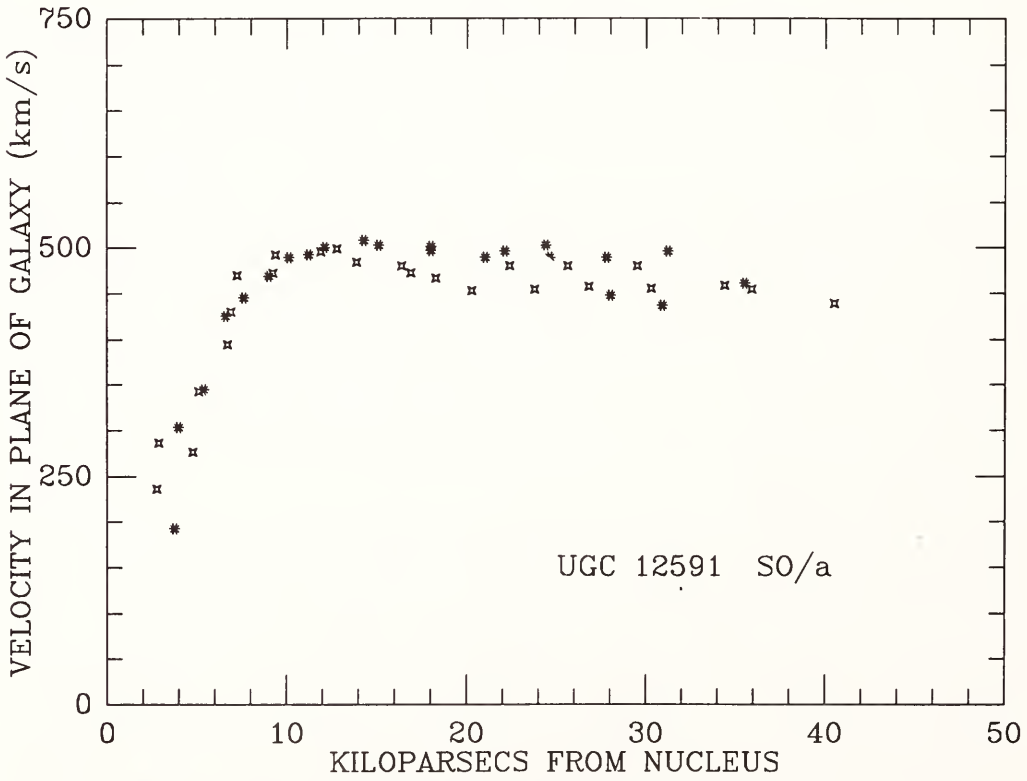
Rotation curves have long been used as indicators of the distribution of a galaxy's mass. The often-cited studies of spiral galaxies by Rubin and Ford revealed that in all cases, more mass was present in a galaxy's outer regions than was indicated by the galaxy's visible image. Now, Rubin and Burstein have classified spiral galaxies into three types according to their mass distributions. Those having Type I mass distribution exhibit rotation curves that rise rapidly near the center of the galaxy and continue to rise slowly at large radii. Type I's are thus greatly influenced by unseen matter in the outer regions, especially matter in the expansive halo surrounding the visible galaxy. Those having Type III mass distribution have rotation curves that rise slowly at small ra-

dii and fall slightly at larger radial distances. (Type II galaxies are intermediate.)

Of the 57 noncluster galaxies studied, 28 are Type I or nearly so; of 20 cluster galaxies studied, none are Type I. Rubin and Burstein believe that this result is evidence that in the denser cluster environment, halos may have been stripped or may have been prevented from forming fully by the nearby presence of halos surrounding other cluster galaxies.

The study has also shown that spirals of each mass-distribution type are found in all Hubble classes and in galaxies of all luminosities. Sa spirals (enormous bulges and small disks) can have rotation curves identical in form to curves of Sc galaxies (prominent disks and negligible bulges). Thus, the dark rather than the visible matter plays the dominant role in determining galaxy dynamics. Of all the parameters that Rubin and Burstein examined, only the environment—cluster or noncluster—exhibits relation to mass-distribution type.

Motions in spiral galaxies also have attracted the attention of James Fillmore of Caltech, Todd Boroson of the University of Michigan, and Alan Dressler of the Mount Wilson and Las Campan-



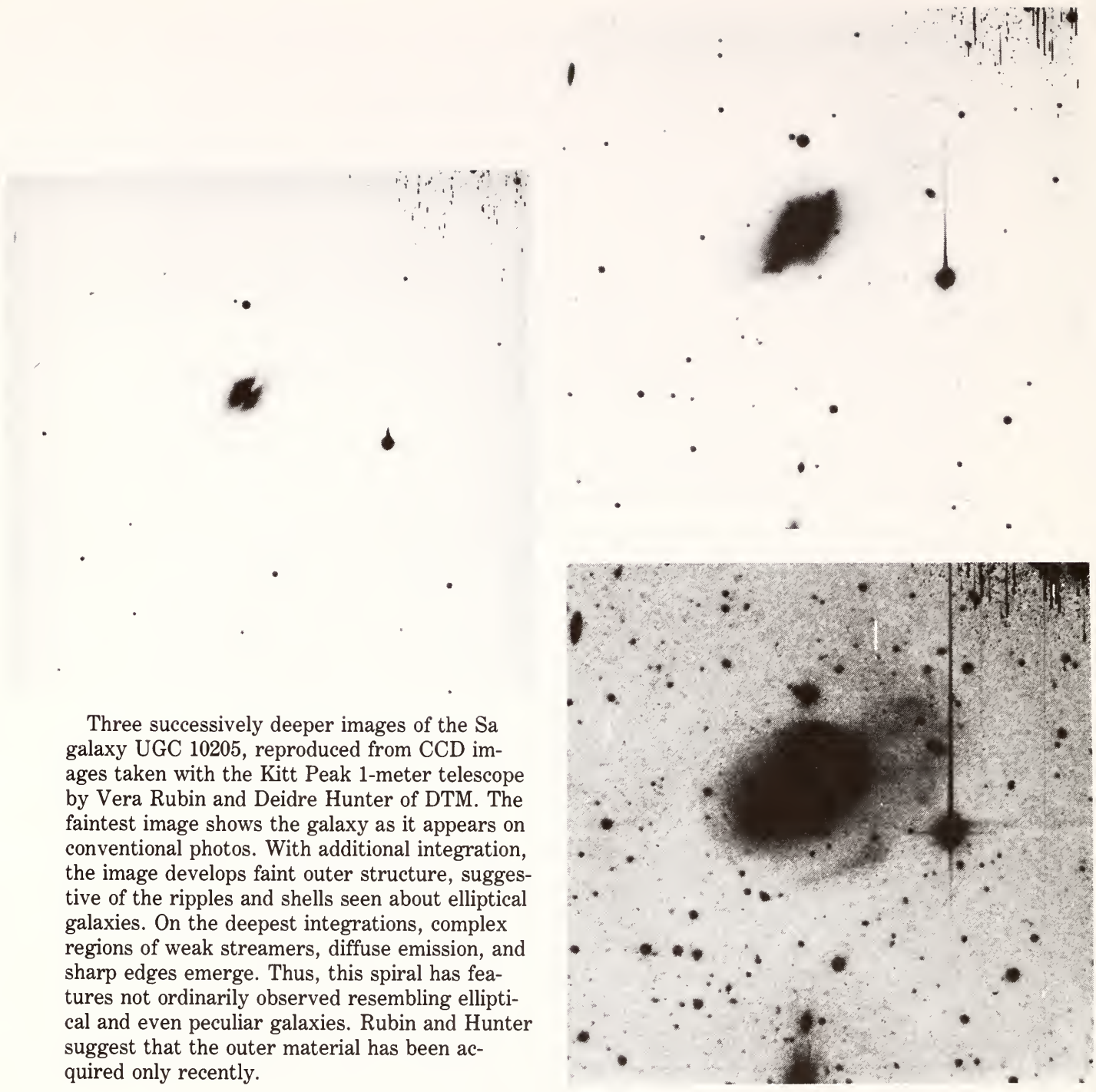
Rotational velocities as a function of radius from the center of the spiral galaxy UGC 12591. The peak rotational velocity, 505 kilometers per second, is the highest known. The observations were obtained at the Palomar 5-meter telescope by Vera Rubin and W. Kent Ford of DTM, with Paul Schechter of the Observatories.

as Observatories. Using CCD detectors at the 5-meter Palomar telescope, they obtained spectra of the inner regions of several spirals, where disk and bulge components overlap. From the spectra, Fillmore, Boroson, and Dressler measured stellar and gaseous rotational velocities, as well as velocity dispersion (a measure of the random, nonrotational motions). Generally speaking, gaseous disk components exhibit rotational motions, and random motions are associated with the bulges. The investigators, however, found it problematic to deconvolve the motions of the disk and bulge components in the inner regions. They did, however, conclude that gaseous rotation is less prominent than expected—apparently a result of noncircular motions in gas released by red giant stars in the bulge.

DTM's Rubin and Ford, helped by Paul Schechter in their observing at Palomar, have obtained rotation curves of several faint galaxies of special interest. In the case of UGC 12591, a fairly isolated spiral, the investigators determined a peak rotational velocity of about 500 kilometers per second—a value much larger than the previously known highest velocity (367 kilometers per second, in NGC 4594). Despite the fast rotation, however, the mass, both dark and luminous, within the visible galaxy is only 2×10^{12} solar masses, a value not significantly greater than that seen in certain other massive spirals. The new observation thus appears to define how much dark matter can be contained within the visible region of a galaxy.

How Different Are Ellipticals and Spirals After All? Rubin and DTM postdoctoral fellow Deidre Hunter report that faint outer features like those recently discovered around elliptical and S0 galaxies, are also present in at least one spiral. Rubin and Hunter have discovered extensive weak outer structure in UGC 10205, an Sa galaxy previously studied by Rubin and colleagues for its rotational properties. The galaxy has a prominent luminous bulge and a disk seen principally in absorption against the bulge. Deep red CCD images taken with the 1-meter Kitt Peak telescope reveal an extensive nonsymmetric envelope, with streamers, condensations, and sharp-edged features. Thus while UGC 10205 appears to be a normal Sa from its conventional photographic images, it has properties like some ellipticals at faint light levels, and it turns into a pathological specimen at the faintest levels.

UGC 10205 is a relatively isolated galaxy; its flat or slightly falling rotation curve (Type II) is not surprising considering its complex outer structure. Rubin and Hunter note that the dynamics of the underlying Sa galaxy have not yet been severely distorted, and that it is likely that the galaxy has only recently acquired the outer material, of which little has yet settled into the disk.



Three successively deeper images of the Sa galaxy UGC 10205, reproduced from CCD images taken with the Kitt Peak 1-meter telescope by Vera Rubin and Deidre Hunter of DTM. The faintest image shows the galaxy as it appears on conventional photos. With additional integration, the image develops faint outer structure, suggestive of the ripples and shells seen about elliptical galaxies. On the deepest integrations, complex regions of weak streamers, diffuse emission, and sharp edges emerge. Thus, this spiral has features not ordinarily observed resembling elliptical and even peculiar galaxies. Rubin and Hunter suggest that the outer material has been acquired only recently.

Do Galaxy Mergers Make Ellipticals? Carnegie's Alan Dressler and George Lake of Bell Laboratories completed a study of possible merging galaxies drawn from the Arp atlas of peculiar galaxies. Their aim was to examine whether the Faber-Jackson relation, which links velocity dispersion and luminosity in ellipticals, also holds for these supposed mergers. They noted that although the outer parts of the merging galaxies were chaotic, their inner regions may well have reached steady condition, since the time for equilibrium to have occurred is relatively short, $\sim 10^8$ years; thus, evidence of the Faber-Jackson relation in the inner regions would be indication that these galaxies have begun evolving into ellipticals.

Dressler and Lake conclude that the inner regions indeed do match the Faber-Jackson relation, and that the merging galaxies will probably be seen as ellipticals in about 10^9 years. They note that certain computer simulations of merging galaxies predict otherwise, but that such simulations are limited by the relatively few stars contained in each computer-galaxy. Thus these simulations predict merged galaxies having too little velocity dispersion per unit mass, and too much ordered, rotational motion. The investigators offer that "Nature is able to make mergers that are sufficiently hot, even if present-day simulations cannot."

The True Shape of Ellipticals. There is no sure way of distinguishing an elliptical's true extent of flattening. A highly-flattened oblate shape (a pancake), seen edge-on, looks the same as a cigar-shaped, prolate body, for example. Or, a cigar seen end-on would look like a sphere. The discovery of the polar-ring galaxies at first raised the thought that these were prolate "spindles," whose disk and ring rotated about the same axis. But this was later shown to be incorrect, and to date no prolate-shaped galaxies have been positively identified. Theory, however, predicts that prolate galaxies can exist, and indeed that there can be "triaxial" galaxies—three-dimensional shapes with three unequal axes.

For there to be three unequal axes, or triaxiality, there would have to be rotational motion along the apparent minor axis of an elliptical. But since the true orientation of any galaxy to the line of sight is unknown, a large number of galaxies must be investigated and the results treated in a statistical fashion. Even so, it is necessary that the directions of the apparent major and minor axes be known very accurately; this requires precise measurements of light intensity at many places in the galaxy's image.

Postdoctoral fellow Robert I. Jedrezejewski and Paul Schechter at the Observatories have begun such an investigation. They have obtained CCD frames of a large sample of ellipticals having the optimum flattening, and they have performed ellipse-fitting using software developed earlier for Jedrezejewski's thesis. One of the main surprises was that, of the sample of forty galaxies, most show isophotal twists, i.e., their contours of constant light are not concentric or even aligned—a result which itself suggests that triaxial galaxies may be common. A prime sample of some ten galaxies was identified, and spectra of six of these were obtained at the 5-meter telescope at Palomar. Very small rotational velocities, of order 30 kilometers per second, must be measured, so the investigators developed special procedures to eliminate distortions in the detecting system. Reduction of the spectroscopic data is in progress.

Galaxy Evolution in Clusters: A New Insight

> The eye-brain combination of an experienced, gifted researcher can assimilate the myriads of details . . ., can recognize recurrent patterns, connect form with process, and leap to generalizations that would resist discovery by the numerical or analytic methods now available at computers.
>
> George W. Preston, Director
> Mount Wilson and Las Campanas Observatories
> July 1985

S0 galaxies are, in several characteristics, intermediate between spiral and elliptical galaxies. Their central bulges are more prominent than those of spirals, they have barely distinguishable disks, and there is relatively little gas available to sustain star formation. They resemble ellipticals in visual appearance but they have greater ordered, rotational motion. Astronomers have long asked whether S0's have in some manner evolved from one of the other types. During the last decade, for example, a widespread notion has been that S0's in rich clusters of galaxies are produced by the stripping of gas from the disks of ordinary spirals.

In an essay prepared for publication in the forthcoming Annual Report of the Mount Wilson and Las Campanas Observatories, staff member Alan Dressler offers fresh thoughts on this question. He first notes that in 1980, he himself put forth evidence against this hypothesis; at that time, he compared bulge size and luminosity of S0's and spirals, and he concluded that stripping a typical population of spirals would yield many small-bulge S0's, not S0's having the large bulges actually seen.

Since 1980, Dressler writes, evidence has been accumulating that spirals in rich clusters are indeed subject to some process that reduces their supply of disk gas, and he cites a forthcoming article where Riccardo Giovanelli and Martha Haynes, both of Cornell, report that a significant number of spirals are found to be deficient in neutral hydrogen gas. Where the galaxy population is dense, the spirals are generally more depleted in gas. Giovanelli and Haynes, however, were unable to correlate gas deficiency with a galaxy's velocity within its cluster (as shown by its radial velocity, measured toward or away from us). Since stripping by ram pressure—that exerted on disk gas when it collides with hot intracluster gas at high speed—should strongly depend on velocity, the data discouraged the idea that such stripping was the mechanism of gas depletion.

Now, Dressler has reexamined the Giovanelli-Haynes data and found two correlations suggesting that ram-pressure stripping may indeed be at work. First, he shows that gas deficiency correlates

with galaxy type—i.e., that Sa and Sb spirals are much more likely to be gas-deficient than types Sc, Sd, or Irr I. The pattern is seen among galaxies in both inner and outer regions of clusters, and in clusters having many depleted galaxies and in clusters having few. Dressler investigates, and rejects, the possibility that the pattern is caused by selection effects, where Sa's and Sb's are more common in denser regions. The apparent correlation with galaxy type, Dressler notes, raises an earlier idea, proposed by another investigator, that gas is removed easily from Sa's and Sb's where gas pressure and rate of replenishment by stellar evolution are lowest. The idea that S0 galaxies may evolve from gas-deficient Sa's is consistent with Dressler's earlier finding that there are few S0's with small bulges.

Dressler also uses the Giovanelli-Haynes data to make a still-different case for ram-pressure stripping. Although gas deficiency and radial velocity could not be correlated earlier, the picture changes if projection effects and the shape of the orbits are more fully considered. Dressler attempted to determine whether orbits were circular or noncircular by examining the dispersal, or scatter, in radial velocity among galaxies at a given apparent radius from a cluster's center, and how this dispersal changes with radius.

Dressler showed that the dispersal in velocity *decreases* with increasing radius—evidence of noncircular orbits—in the case of *gas-poor* spirals. Such orbits brought these galaxies, therefore, occasionally close to the cluster core, where the dense environment is conducive to ram stripping. On the other hand, he showed that dispersal in velocity among gas-rich galaxies *increases* with radius, so that these galaxies were on circular orbits. These spirals, thus, had never passed close to the core, had not been subject to ram stripping, and had therefore retained their gas.

It is not yet clear, Dressler writes, whether his correlation between galaxy type and gas deficiency is the result of a more fundamental correlation between type and orbital characteristic; one difficulty is that there are too few gas-poor, Sc and Sd spirals available for study. It appears, however, that two conditions must be met for a spiral to be stripped: (1) it must be on a plunging orbit that takes it close to cluster center, and (2) it must be a type Sa or Sb, which are more easily stripped than Sc or Sd types. Although still other questions remain unanswered, Dressler concludes: "It is becoming increasingly clear that spirals are subject to environmental effects that change their gas contents and star-formation histories. . . . As for over ten years, the leading candidate remains ram-pressure stripping by a hot intracluster medium."

Galaxies at Very Large Redshifts

Carnegie fellow Rogier Windhorst at the Observatories has

collaborated with former DTM fellow David Koo, now at the Space Telescope Science Institute, and several other investigators, in a series of observations of very distant objects, seen at the limiting faintness of today's most advanced optical systems. The ability to observe at very faint magnitudes allows cosmologists in effect to look backward in time; objects seen at large redshifts are seen as they were much earlier in the Universe, and provide data for projecting even farther backward to earliest epochs.

It is fundamentally important to cosmologists to learn when in the early Universe galaxies and radio sources began to form. Important clues lie in present-day observations of radio sources at substantial redshifts, which allow analyses indicating the probable maximum distance, or time era, of such objects. Two conflicting views have emerged on this point. One group of investigators, working from luminosities and redshift distributions of observable radio sources, predicts that there should be a substantial fraction of radio sources at the extremely large redshift of $z = 5$. Others have argued mainly from optical data and spectroscopy, that the brighter radio sources need extend only to about $z = 2.5$. (A z value of 2.5 corresponds to an age of about 3.5 billion years, roughly a fifth the age of the Universe, for reasonable values of the cosmological parameters, $H_0 = 50$ and $q_0 = 0.1$.) Windhorst, who favors the lower value of z, notes that the triggering of the first radio source in a galaxy may have occurred some time after initial star formation.

Windhorst, with various collaborators including Koo, has in recent years conducted ultradeep radio surveys with the Westerbork Synthesis Radio Telescope in The Netherlands, and with the Very Large Array radio telescope, New Mexico. About half of the radio sources have been identified optically, and these tend to fall into two distinct categories. The galaxies having the brighter radio sources tend to resemble bright, giant ellipticals with rather large redshifts $z \leqslant 0.8$. The fainter ("microJansky") radio sources largely form a different class of blue galaxies, having lower optical luminosity and intermediate redshift $z \leqslant 0.5$, and they resemble interacting or merging galaxies in form.

Windhorst and Koo selected a subsample of several dozen faint radio sources not previously identified optically. Working at the 5-meter Palomar telescope equipped with the Four-shooter CCD, they attempted ultradeep identifications. (The Four-shooter is highly efficient for this work, because a single exposure covers an area of 9×9 minutes in one exposure and can thereby capture perhaps a dozen microJansky sources.) Windhorst and Koo easily identified the eleven microJansky sources in the subsample to the faintest optical magnitude of 24.5. Of the 52 brighter radio sources, however, they were able to identify only 43, though one of them was identified at the extremely faint magnitude 25.3.

The identification of all the microJansky sources suggests that the

associated blue, radio-galaxy class need not extend to redshifts very far beyond $z = 1$; this is a considerably lower value than previously proposed. Meanwhile, the inability to identify all the giant red elliptical radio galaxies suggests that these objects may extend to much greater redshifts. Ultimately, such questions must be answered by still fainter identifications and, especially, by spectroscopy.

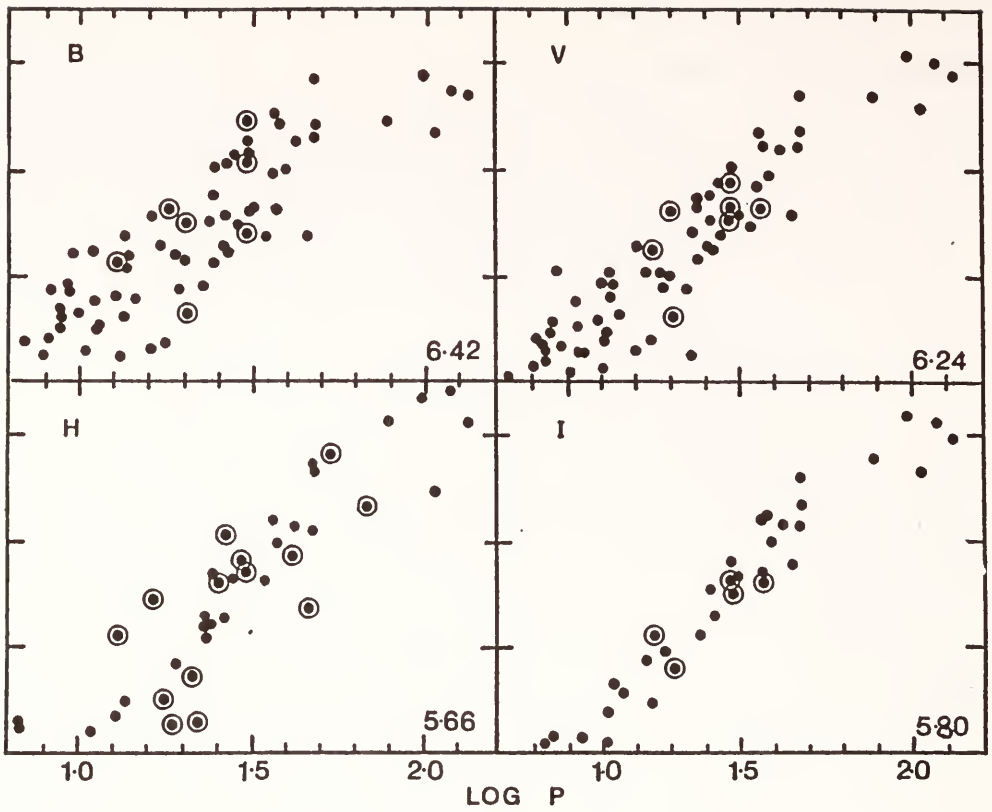
Toward a Cosmological Distance Scale

Wide disagreement over extragalactic distances remains a central matter in astronomy. Early in this century, scientists established that the period of pulsation of a Cepheid variable star was a direct indicator of the star's intrinsic luminosity. Its distance from us could then be determined by comparing intrinsic and apparent luminosity (correcting for extinction of light in intervening space). Cepheids became a key yardstick for determining distances to nearby galaxies, and they remain important for testing and calibrating other yardsticks that might then be extended to more-distant galaxies.

Seeking fresh refinement of the Cepheid period-luminosity relation, postdoctoral fellow Wendy Freedman at the Observatories has obtained CCD photometry for known Cepheids in the nearby galaxy M33. The use of linear, CCD detectors allowed photometry at fairly long wavelengths, where the effects of reddening and metallicity are lower than in the wavelength region where Cepheid studies have traditionally been carried out.

Freedman's M33 Cepheid data, plotted with measurements of Cepheids in the close-by Large Magellanic Cloud (LMC), exhibited very narrow scatter. Consistency was especially strong at the longer wavelength $I = 0.9$ μm. The data at four wavelengths yielded an estimate of extinction of $A_v = 0.6$ mag, and a preliminary true distance modulus (intrinsic minus apparent magnitude) of 24.1. This value is lower than values determined recently by other investigators, perhaps because of different approaches to internal absorption and LMC modulus. The program is now being applied to known Cepheids in other nearby galaxies.

Meanwhile, Allan Sandage has continued his studies of the color-magnitude diagrams of nearby galaxies containing Cepheids, with the goal of refining and calibrating a distance scale based on a galaxy's brightest red and blue stars. With George Carlson (Citrus College), Sandage has found and measured Cepheids in the galaxies Sextans B and WLM, yielding distances to these two galaxies and leading to values of intrinsic magnitude for the three brightest red and blue stars in each. In these two galaxies and in eleven other calibrating galaxies, the investigators explored relations between brightest-star magnitude and parent galaxy intrinsic luminosity.



Postdoctoral fellow Wendy Freedman has obtained CCD photometry of Cepheids in the nearby galaxy M33. Here, period of Cepheid pulsation is plotted against apparent magnitude at four wavelengths; M33 stars are encircled, stars of the close-by Large Magellanic Cloud (LMC) are not circled. Vertical scale is adjusted to bring M33 and LMC plots to approximate superposition. The derived distance modulus (intrinsic minus apparent magnitude) of M33 minus that of LMC is shown at the bottom right of each plot. (In each galaxy, all Cepheids are at essentially the same distance.) The differential values as a function of increasing wavelength allow an estimate of the total extinction in intervening space to be obtained; the traditional Cepheid period-luminosity relation can now be applied with a more accurate correction for light extinction.

The luminosity of a galaxy's brightest stars holds promise as a possible yardstick out to substantial distances (100 Mpc), especially when observations become possible using the Hubble Space Telescope. The galaxies that are suitable for this work with the Space Telescope are fairly rare, constituting only about 15% of any complete sample at a given magnitude. Required are star-producing galaxies having disks of low surface brightness, which allow measurement of the embedded stars to magnitude 25 in the visual wavelengths and 27 in the blue. Sandage and Observatories' photographer John Bedke, now at the Space Telescope Science Institute, have prepared photographic atlases containing 157 galaxies deemed suitable for this future work. The Space Telescope observations may settle the long-standing disagreement over cosmological distances.

Still another approach to the distance scale is seen in the current supernova search organized by Sandage and colleague Gustav Tammann of the University of Basel. Type I supernovae have been used as standard candles for determining the distances to oth-

er galaxies. The purpose of the present investigation is to determine how widely they can be found. Ninety search fields have been selected, each rich in elliptical galaxies, which are known to be slow supernova producers but which absorb supernova light only minimally. The search is being conducted at the 1-meter Swope telescope at Las Campanas by students from the Astronomical Institute of the University of Basel. During the year, they discovered a total of five new supernovae; a conclusion as to the overall frequency of their occurrence has not yet been reached. The effort is funded by the Swiss and the U.S. National Science Foundations.

The Heavy-Element Contents of Stars: Further Keys to Galaxy Evolution

The urge to understand galaxy formation and evolution, seen in the various investigations of galaxy interactions and mergers, is also evident in ventures by those astronomers who study the stars of our own Milky Way Galaxy and its close neighbors. Varied current work on heavy-element, or "metallicity," gradients within the Galaxy, for example, is testing the traditional picture that the Milky Way formed as the product of a collapsing cloud.

Indeed, these ventures in stellar astronomy are pointing toward the same questions being asked in extragalactic studies. To what extent are the galaxies seen today, including the Milky Way, products of (1) collapsing primordial clouds or (2) interactions among earlier galaxies? (It now seems clear that both processes have been at work, but the details of neither process are well agreed.) As evidence steadily accumulates, we are witnessing how science seeks and uses new findings—sometimes seemingly contradictory in their directions—gradually to tighten existing theories until eventually a new synthesis emerges to refine or perhaps replace the old.

A Search for the Earliest Stars. In the generally accepted picture of how the chemical elements formed, the Big Bang produced only hydrogen and helium (and traces of lithium). The heavier elements were formed later, by nuclear fusion in the centers of stars, which eventually exploded as supernovae, thereby injecting heavy-element-enriched material into interstellar space. Later-forming stars should thus contain some of this enriched material and should now exhibit higher heavy-element concentrations than would the earliest stars, which presumably formed from nearly primordial material very low in the heavy elements.

Massive stars evolve rapidly to the final supernova stage, and therefore contribute heavily to heavy-element enrichment. Stars less massive than 0.8 Suns, on the other hand, evolve so slowly that they can survive from the earliest epoch of star formation to the present day. If such stars were among the early

generations of stars, then some of them—still exhibiting nearly primordial metal abundance—should be observable today.

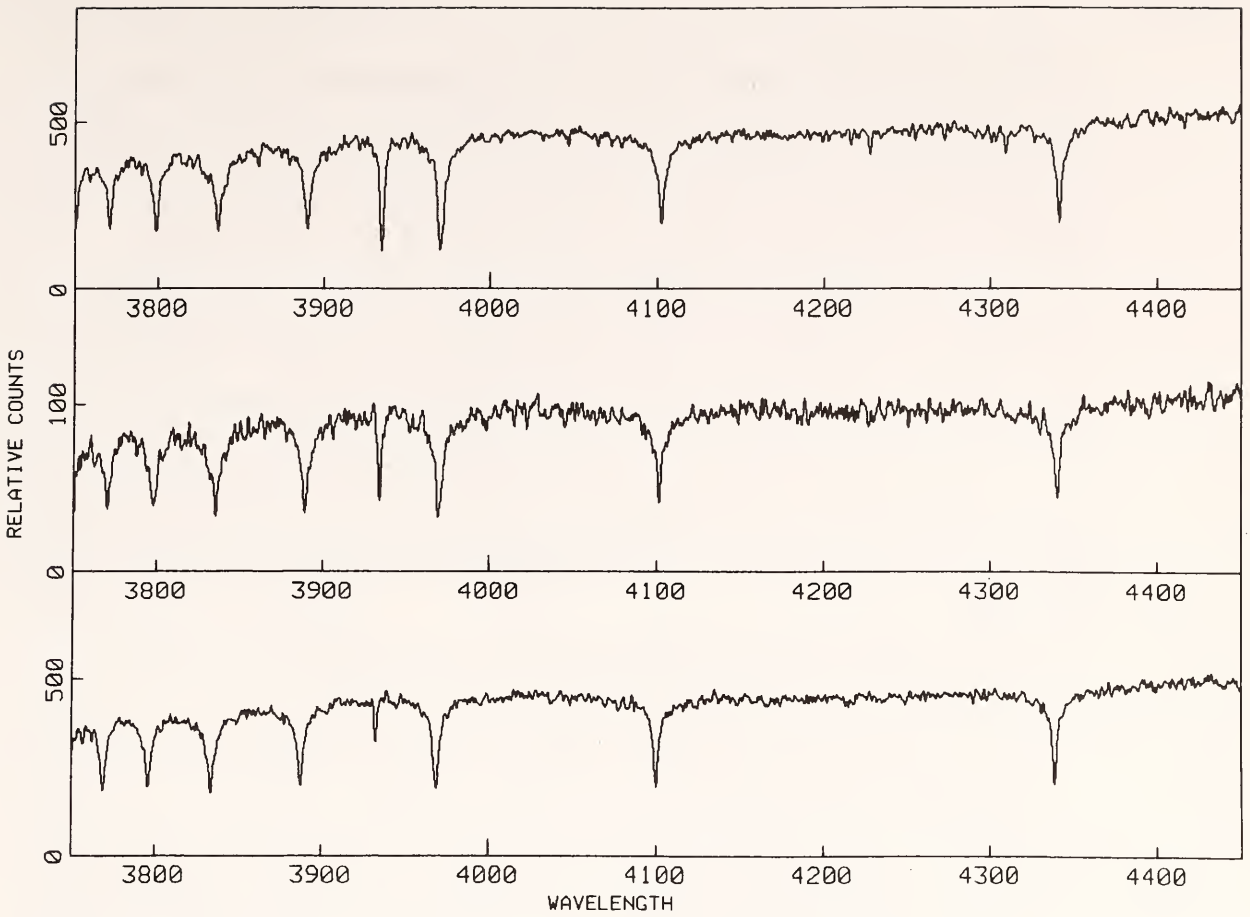
The place to search for these low-metal stars is in the halo of our Galaxy, whose stars are primarily old ones having heavy-element abundances only 1–10% that of the Sun. (In the scale usually used, the element iron represents the heavy elements; such stars have values of [Fe/H] between -2.0 and -1.0.) In the simplest model for supernova enrichment in this range, low-metal stars should be rare: of 100 stars having [Fe/H] < -2.0, only ten are expected with [Fe/H] < -3.0, and only one with [Fe/H] < -4.0.

The questions remained: could stars having these metal abundances be observed in the halo of our Galaxy, and would they be found in the appropriate distribution? Conceivably, low-mass stars were not among the early generations, or perhaps the earliest stars were formed ahead of the Galaxy and are scattered through intergalactic space.

To test these questions, Stephen Shectman, George Preston, and Timothy Beers of the Observatories several years ago launched a search for stars of very low metal abundance. Their first step was at the 61-cm Curtis Schmidt telescope at Cerro Tololo Inter-American Observatory, Chile, where they obtained some eighty survey plates, each covering a sky area of 5×5 degrees; the plates were obtained through an objective prism and an interference filter designed to admit principally the wavelengths of the H and K lines of Ca II (3968 Å and 3933 Å)—the strongest absorption lines in the spectra of normal stars. Each plate contained thousands of spectra of stars; most exhibited the strong H and K absorption typical of normal stars. But a few stars per plate exhibited weak or absent H and K. These became the low-metal-abundance candidates, and about 1800 were found on the eighty plates.

Next, using spectrographs on the Las Campanas 2.5-meter du Pont telescope and the Palomar 5-meter Hale telescope, the investigators obtained detailed, higher-resolution spectra individually from many of the candidates. The typical spectrum of a low-metal star exhibits only the Balmer lines of hydrogen, the weak calcium H and K, and perhaps the G band, a molecular feature caused by CH. Shectman *et al.* measured the line strengths by comparing the flux in a wavelength interval centered on each line to the flux in nearby continuum intervals. The hydrogen line strength increases with temperature and provides a measure of the star's surface temperature. The strength of the calcium K line, which decreases with temperature, has been calibrated from stars of known metallicity in globular clusters and in the field. Using this calibration, the investigators have analyzed 450 spectra of metal-poor candidates. The result is their present sample of 134 stars having [Fe/H] < -2.0.

The investigators then obtained broad-band photometry of the



Spectra of three candidate low-metal-abundance stars, from the search by Stephen Shectman, George Preston, and Timothy Beers of the Observatories for stars of low metallicity. The star at the top is marginally metal poor at [Fe/H] = −2.0, as indicated by the moderately strong absorption of the K line at 3933Å. The middle spectrum exhibits less-pronounced K-line absorption and is therefore lower in metal abundance. The star at the bottom has the weakest K-line absorption, and thus has heavy-element abundance probably 10,000 times lower than the Sun. The lower star may therefore be a primordial star remaining from the early population of our Galaxy.

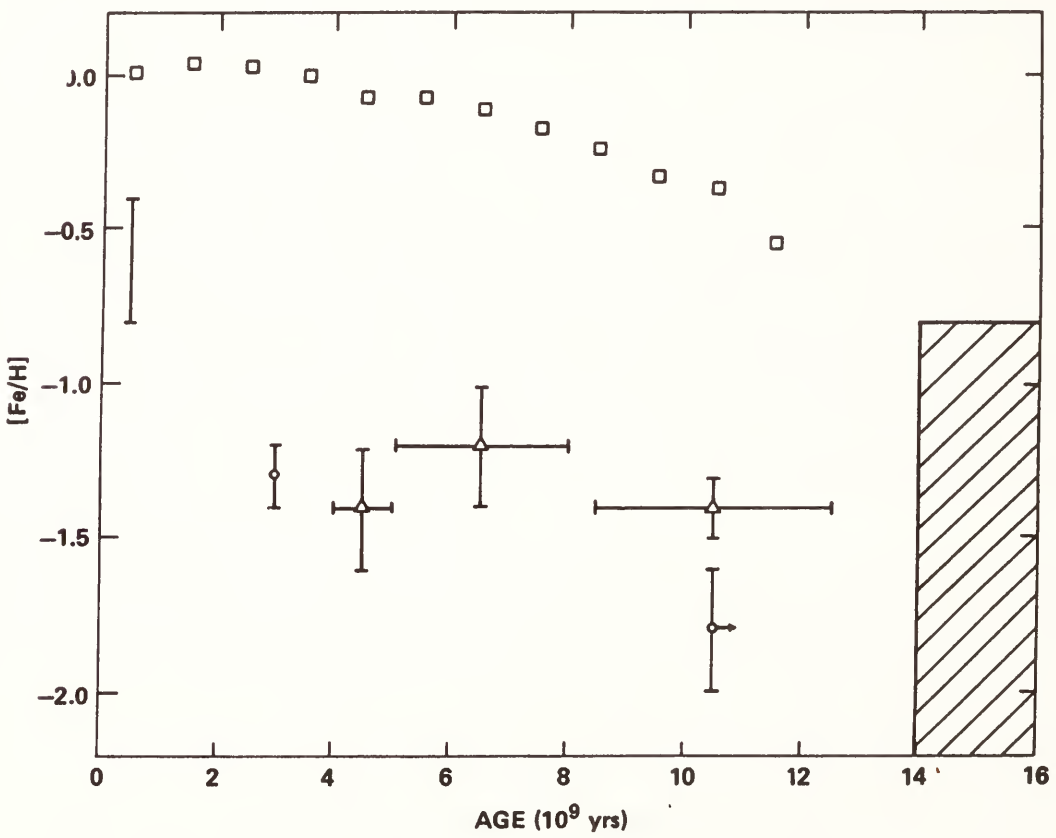
metal-poor sample using the 1-meter Swope telescope at Las Campanas, thereby discriminating among various classes of stars—unevolved dwarfs, evolved giants, and still-more-evolved giants—the same classes seen in metal-poor globular clusters.

Shectman notes that five stars in the sample of 134 appear to exhibit heavy-metal abundances of [Fe/H] < -3.5. Only one star of lower abundance has ever been discovered. Although such stars are rare and difficult to find, he concludes, they seem to occur with sufficient frequency to be consistent with simple models of chemical enrichment during the early formation of the Galaxy. The numbers predict that the numbers of stars produced increase in direct proportion to their metallicity. A strong statement about agreement between theory and observation will require enlargement of the sample of metal-poor stars.

Chemical Evolution in the Small Magellanic Cloud. The Small Magellanic Cloud (SMC) is a close-by irregular galaxy, a satellite to the Milky Way. To learn about its chemical evolution, DTM

postdoctoral fellow Linda Stryker and Horace Smith of Michigan State University, a former fellow at the Observatories, last year used the 2.5-meter du Pont telescope at Las Campanas to study compositions of three types of pulsational variable SMC stars, each formed in a different epoch of the galaxy's evolution. They observed the old ($>10^{10}$ years) RR Lyrae, the intermediate-age anomalous Cepheids, and the young (0.5×10^3 years) Wesselink-Shuttleworth variables. From the present-day compositions of these stars, Stryker and Smith found that chemical processes in the SMC have proceeded much more slowly and shallowly than in our Galaxy; only in recent times ($< 2 \times 10^9$ years) has the SMC reached the level of enrichment in elements heavier than hydrogen and helium that the disk of our Galaxy attained 10×10^9 years ago.

Stryker, with Jeremy Mould of Caltech and Gary Da Costa of



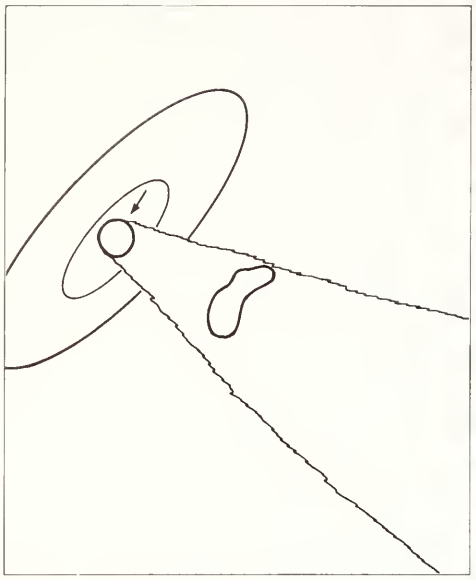
DTM postdoctoral fellow Linda Stryker and Horace Smith of Michigan State have studied chemical evolution in the Small Magellanic Cloud, a satellite galaxy of the Milky Way. Plotted here are the heavy-element abundances, shown as the ratio [Fe/H], and ages of several types of SMC stars (triangles, circles). The bar at left represents the youngest SMC objects. The squares are stars of our own Galaxy. Notice that in both the SMC and our Galaxy, younger stars are higher in Fe than old ones. Chemical evolution toward higher heavy-element content has clearly proceeded less fully in the SMC than in our Galaxy; only in the last 2×10^9 years has SMC heavy-element content reached the level of our Galaxy 10×10^9 years ago. (The shaded box represents globular clusters of our Galaxy.)

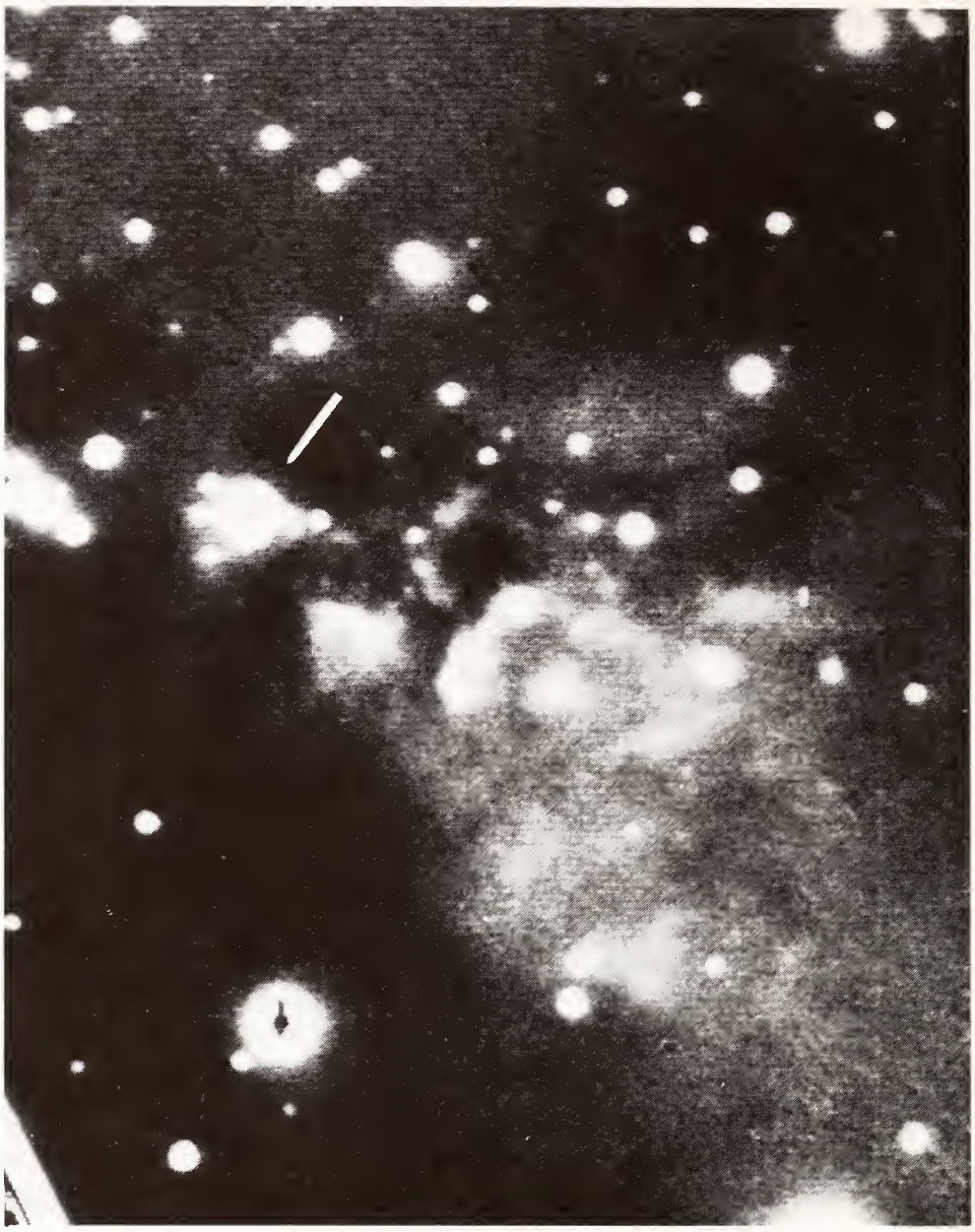
Yale, is also studying NGC 121, the oldest known globular cluster of the SMC. The observations, obtained at the 4-meter Cerro Tololo telescope in Chile, further support the hypothesis that chemical enrichment occurred in the SMC relatively recently. Meanwhile, another group of investigators, including Nicholas Suntzeff of the Observatories and John Graham, then of Cerro Tololo Inter-American Observatory, began a study of the SMC halo population. Graham's plates from an earlier study of RR Lyrae stars in the halo, along with newly obtained plates, were used to identify star motions and weed out foreground stars of our Galaxy. Spectra of about twelve red giants of the SMC halo were then obtained, and direct CCD frames were taken of the region near NGC 121. Suntzeff, Graham, and colleagues concluded that the SMC halo stars are somewhat poorer in heavy elements than the average halo stars of our Galaxy.

Evidence from Globular Clusters of Our Galaxy. The globular clusters of our Galaxy are composed of older stars, which formed early in the collapse and are therefore low in heavy-element content. Many of the globulars are to be found in the halo, where their orbital motions fail to provide a systematic rotational pattern. How their composition varies with orbital distance from Galaxy Center has been studied by Leonard Searle of the Observatories and Robert Zinn of Yale University, seeking insights into the early chemical history of the Galaxy.

In the current year, Nicholas Suntzeff, in collaboration with Edward Olszewski of Steward Observatory and Peter Stetson (formerly a Carnegie fellow and now of the Dominion Astrophysical Observatory), has obtained spectra of red giant stars in AM-1, the most distant globular associated with our Galaxy. The measured heavy-element abundances support the absence of a metallicity gradient in extreme outer regions of the Galaxy. (The investigators also note that the low orbital velocity of AM-1 fails to provide evidence of the presence of substantial dark mass in the outer regions.) The observations were made with the Reticon spectrometer at the du Pont telescope, Las Campanas.

Rotation vs. Heavy-Element Content. Allan Sandage and research assistant Gary Fouts (now of the Space Telescope Science Institute), completed radial velocity measurements of a large population of high-proper-motion stars. During some three years, they obtained over 2200 measurements with the Mount Wilson 2.5-meter telescope using the coudé spectrograph and the Reticon spectrometer. Space motions have been computed from the Doppler-shift measurements and the proper motion of each star, and correlations were developed between the rotational velocities about Galaxy Center and the metal abundances previously determined by color photometry.





S. Eric Persson and Belva Campbell of the Observatories are studying the Young Stellar Object (YSO) GL490. In this remarkable view of the region, the apparent GL490 central object is marked. To its lower right is seen a vast region of nebulosity—apparently a cone of emission representing a powerful outflow moving away from the center at an angle toward the observer. (A similar outflow on the opposite side of the central object is obscured by the interior of the molecular cloud and by a large and dusty molecular disk, evidence for which is found in radio observations and in the several large and prominent dark areas near the central object.) A bowed structure seen in the cone could be emission from the shock-heated edge of a clump of gas locally blocking the outflow or light reflected from the central source. The image was obtained in the near-infrared (8200Å) with the Four-shooter CCD system at the Palomar 5-meter telescope. Seen in the field are numerous nearby stars, including several seen at the edge of the YSO image. (The scaled drawing at top left indicates location of central object at arrow, the cone of outflow, the bowed structure therein, and the molecular disk.)

The principal result is that the rotational velocity of the stars about Galaxy Center is a strong and monotonic function of the metal abundance. The lower the heavy-element content in a given star, the lower the star's rotational velocity. The result is consistent with the collapse model of formation of the Galaxy, where a gas cloud's spin increases as the collapse proceeds so that stars forming late rotate faster and have higher metallicities; this result differs from results in studying globular clusters in M31, where rotational velocity and heavy-element abundance exhibit no correlation.

The Process of Star Formation

Stars are formed of the gas and dust in a galaxy or pre-galaxy, generally in regions of higher-than-average mass density. Although the actual birth of a star cannot be observed optically inside the clouds of molecular hydrogen where birth occurs, improved methods for observing in the infrared are starting to give significant insights. In addition, observations in the optical using CCD's are becoming feasible in regions where young stars are emerging from their inner-cloud birthplaces.

A Prototypical Young Stellar Object (YSO). The advent of CCD spectrometers and direct cameras has opened the way for accelerated study of massive, new stars emerging from their natal clouds. Last year, Observatories staff member S. Eric Persson reported spectroscopic observations of the prototypical Young Stellar Object (YSO) GL490—a bright infrared source exhibiting an extended and powerful, bipolar outflow of molecular gas (*Year Book 83*, pp. 60–63). Despite its complexity, the source region provides considerable insight into the processes of star formation in general.

This year, Persson and postdoctoral fellow Belva Campbell began a study of the GL490 region in the optical and near-infrared regions, employing the Four-shooter CCD camera system at the 5-meter Palomar telescope. The system gives high sensitivity, a large field of view (9 minutes square), and an image scale allowing precise positioning.

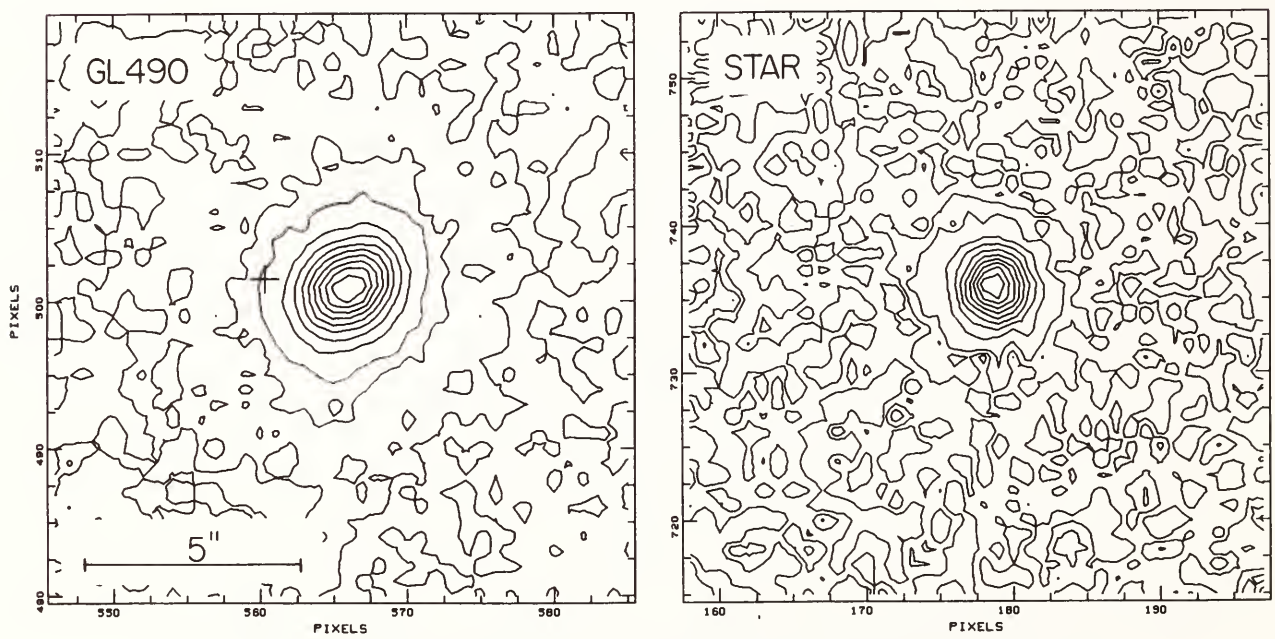
The investigators obtained images in several wavebands. Presented on the opposite page is a deep exposure showing the structure around the central source. Described in the legend are the significant features—the apparent central source, a large conical outflow, a barlike structure crossing the outflow, and several large dark areas surrounding the central source.

The dark areas appear to be clouds of intervening material near the source itself. These correspond well to peaks in radio emission, which reveal the existence of a massive molecular disk slowly rotating around the core. The disk obscures emissions in the optical: indeed, the investigators believe that the visible central

source is in reality an image in scattered light, which is emerging from within the disk via a tunnel. The material pushing on the molecular cloud to create the conical outflow is escaping through the same tunnel. Outflow in the opposite direction (the outflow is bipolar) is obscured.

Contours of equal brightness (see figure, below) reveal the structure of the apparent central source. Shown on the same drawing is the location of the radio continuum source, from radio observations at the Very Large Array in New Mexico. Presumably this represents the actual position of the YSO core, whose direct emissions in the optical and near-infrared are obscured by the disk. Recent theoretical work on outflows suggests that the inner regions of the rotating disk are magnetized and partly ionized by the core source, and that the outflow may occur along helical lines of magnetic field. The flow pattern close to the source and along its exit tunnel may thus govern the apparent image structure. Study at higher resolution from the Space Telescope may delineate this pattern.

In another investigation, Persson and Peter McGregor studied the red spectrum of I Zwicky 1, an active galaxy that has strong



At left, structure of the GL490 central object; contours of equal brightness begin at 90% of the peak value and drop in 10% increments to sky level. The contours are slightly elongated roughly at right angle to the direction of the molecular outflow; systematic rotation of the contours can be noted. A cross marks the position of the radio continuum source, recently measured by Belva Campbell with the Very Large Array radio telescope, New Mexico. The investigators believe that the visual source is being seen in scattered light from within the molecular disk where the YSO is itself embedded (at the radio source position). Geometrical considerations suggest that the image emerges through a trumpet-shaped tunnel, and it is through this same opening that the large-scale molecular outflow is powered.

At right, a corresponding image of a star from the same frame. The YSO structure is considerably more extended and wider than the star's.

Fe II lines. The observations were motivated by the finding that the high-density physical conditions deduced for the envelopes of YSO's, such as GL490, resembled those inferred for the broad-line regions of quasars and Seyfert 1 galaxies. It was found that in several respects the spectrum of the active nucleus of the galaxy was similar to that of GL490, in that several emission lines and blends were common to both. Reasoning that the spectral signatures may indicate not only similar physical conditions but also a common basic geometry for the emission line gas, the investigators speculated that a single "disk plus jet" model may appropriately describe both systems, which differ in energy output and geometrical scale by eight orders of magnitude. Preston observes that it should be fascinating to see if subsequent studies will bear out this idea. Further observations of a larger sample of galaxies do indeed point in this direction.

Star Formation in Irregulars. Deidre Hunter, with Jay Gallagher of Kitt Peak National Observatory and others, is investigating star formation in irregular galaxies. The investigators have explored stellar content by near-infrared photometry and imaging (which is sensitive to older stars) and by ultraviolet spectroscopy (which primarily reveals the massive young stars). Both old and young stars seem fairly normal in the irregulars, suggesting that the basic star-formation processes cannot be drastically different from those in typical spirals. Still, the irregulars do not have the dark dust nebulae or strong CO fluxes commonly associated with star formation in spirals. Hunter and colleagues are using infrared observations from the IRAS satellite and from the Kuiper Airborne Observatory to explore the nature of dust in irregulars; the dust temperatures (from colors) are not very different from those in spirals, so that although the dust content is low, it is sufficient for normal star formation.

Advanced Theoretical Studies of Star Formation. Spectroscopic observations at radio wavelengths, revealing Doppler shifts, are useful in mapping the motions inside interstellar clouds, where star formation may be occurring. In several cases, there is indication that the inner cloud core rotates in a sense opposite to that of the cloud outer envelope. One explanation for this phenomenon has been that magnetic fields have rotationally spun down the cloud so vigorously that the cloud's rotational momentum in the inner region has temporarily overshot the equilibrium point. If so, the retrograde rotation could provide evidence for studying the strength of the magnetic field.

In theoretical work, however, DTM's Alan Boss has found that such motions could be attributable to a nonmagnetic cloud collapse, leading to formation of a binary protostellar system. This interpretation is supported by recent IRAS satellite observations

in the infrared, which detected a protostellar object in the core of a rotating molecular cloud. (If magnetic fields caused the retrograde rotation, it is hard to see how the cloud could have collapsed to form the star.) Boss's model can be tested observationally by searching for a second embedded protostar in the same cloud core.

In studying the question of fragmentation in collapsing clouds during star formation, Boss has conducted various collapse simulations. The programs are designed to ask whether or not dense clouds fragment into single or double protostar systems before reaching a condition where further fragmentation is unlikely. Boss finds that as the mass of clouds is reduced through successive fragmentations, and as protostellar clouds become dense enough to begin heating, thermal effects begin to dominate events. Thermal pressure opposes fragmentation, and at a small enough mass, the protostar no longer fragments but instead forms a single star. Boss hopes to learn how small a star can be that is formed in cloud fragmentation.

Solar-Stellar Physics

The study of other stars yields understanding of our Sun, and vice versa. The Mount Wilson 1.5-meter telescope continues to be devoted to nightly measurements of chromospheric activity in solar-like stars. About a third of the observing time is now devoted to the long-term monitoring of selected stars, including some used by Olin C. Wilson to study long-term variations analogous to the 11-year sunspot cycle. Later investigators detected short-term variations in chromospheric activity attributable to rotation in many stars. Research associate Douglas Duncan of the Observatories leads the present effort, supported actively by Arthur Vaughan, a former staff member now of the Perkin-Elmer Corporation.

The venture is bringing a host of interesting findings. Robert Noyes of the Harvard-Smithsonian Center for Astrophysics, Nigel Weiss of the University of Cambridge, and Vaughan recently published plausible evidence that among stars of a given spectral type (or mass), the period of the activity cycle is nearly proportional to the period of rotation. Further, for all stars regardless of type, the period of the cycle increases with increasing Rossby Number (the ratio of rotational period to the theoretically computed convective overturn time). These empirical results provide a basis for testing theoretical work, and they raise the possibility of studying (with solar-wind and geological data) how solar activity and rotation have varied in the geological past.

Findings of multiple periodicity in certain stars (i.e., different rates of rotation at different stellar latitudes), described in *Year Book 83* (p. 65), have been expanded; measurements of chromospheric emission of Sun-like Hyades cluster stars have been corre-

lated with broad-band photometry for the same stars obtained at Lowell Observatory, in order to deduce the number and size of activity complexes. Duncan is using extensive data on the strength of chromospheric H and K emission to construct the relations between these emissions and stellar age, and with David Soderblum of Space Telescope Science Institute, he is using the resulting relation to infer age distribution of stars in the solar neighborhood. Preliminary indication is that the star-formation rate has been uniform except that a surplus of young stars (age < 1 billion years) is emerging. This surplus may help explain the so-called Vaughan-Preston gap—a deficiency of stars of intermediate age in comparison to young and old stars.

Instruments for Discovery

> We live in an era in which streams of numbers flow from telescopes to signal the capture of photons in various formats—digital images of small patches of sky, one- or two-dimensional spectra, or time-series of flux signals from variable celestial sources. A digital electronic revolution is in progress; there is no question of its power, and no turning back. . . .
>
> George W. Preston, Director
> Mount Wilson and Las Campanas Observatories
> July 1985

The electronic revolution in astronomy arose with the development of electronic image tubes for use at major telescopes in the 1950s and 1960s. A central figure in the work was astronomer W. Kent Ford of Carnegie Institution's Department of Terrestrial Magnetism (DTM). In 1965, DTM's director, Merle Tuve, believing that Carnegie scientists should lead not only in developing the tubes but also in employing them in forefront research, brought astronomer Vera Rubin to DTM to share in this effort. Today, the names of Ford and Rubin are esteemed throughout the profession for their leading research on spiral galaxy rotation, primarily using the Carnegie image tubes. Auxiliary detectors—successors to the Carnegie tubes—are now used in nearly all significant programs in optical astronomy, vastly enhancing the observing power of major telescopes.

During the past year, two instruments of special significance were installed at Las Campanas. Both are detectors capable of imaging in two dimensions; both feature charge-coupled devices (CCD's)—solid-state photodiode sensors. Both were designed and constructed by Stephen Shectman, Christopher Price, and Ian Thompson of the Observatories.

The first instrument, informally called the 2D-Frutti, is a photon-

counter whose CCD is used to locate scintillations caused by individual photons passed through a high-gain image intensifier chain. It replaces the Reticon spectrometer, which had been in use at the Cassegrain focus of the du Pont telescope since 1978. Whereas the Reticons located scintillations in only one dimension, the 2D functions in two dimensions—corresponding to wavelength and position along the spectrograph entrance slit, which can be up to 5 arcminutes long.

The first stage of the image intensifier chain is a Carnegie image tube—a magnetically focused intensifier with excellent resolution and blue response. A transfer lens couples the output of the Carnegie tube to an electrostatic intensifier and a microchannel-plate intensifier, which provide most of the gain in the system. The CCD is coupled to the last stage of intensification through a fiber-optic minifier.

The CCD format is 380 × 244 diodes; the entire array can be inspected every 8 milliseconds. The output of each diode is digitized, and the digital information is used to extract a precise measure of the location of each scintillation. The position of a scintillation, which is typically spread over two or three diodes in both horizontal and vertical directions, is measured to a precision of 1/8 diode by comparing the outputs of the diodes immediately adjacent to the peak. The image is built up by accumulating the value in a digital memory corresponding to the location at which each scintillation is detected. The present capacity of the memory is 1.5 million bytes, or 750,000 locations. The typical format of the image is 3040 elements in the wavelength direction × 256 elements along the slit. The image memory is connected to a minicomputer.

The two-dimensional feature and the added resolution offer many advantages. Sky background can be determined more precisely than before, galaxy rotation and other measurements can be made more efficiently, and two or more objects can be observed simultaneously by advantageous placement of slit assemblies.

The second new instrument is the direct CCD camera. This detector eschews image intensifiers for the very high quantum efficiency of the CCD itself. The unintensified signals are very weak, and stringent demands are placed on output amplification.

The direct CCD is an RCA device with 320 × 512 elements. The chip is cooled in a liquid nitrogen dewar and operates in a vacuum. Most of the electronics to operate the CCD are attached to the outside of the dewar, connected by vacuum feedthroughs. The signal is digitized by a 15-bit analog-to-digital converter.

The minicomputer used to control the CCD camera and to store the resulting images is identical in design to the one used for the 2D-Frutti. A third complete computer system is maintained at Las Campanas as a spare. A vacuum pumping station is used to maintain the dewar vacuum.

The CCD has a much higher dynamic range than the 2D-Frutti (i.e., it can record great ranges in brightness with high accuracy in a single observation), and it is ideal for precise broad-band photometry of extended objects or of many objects in a single field.

The electronic revolution also reaches into other areas of research. Preston finds a striking example in the use of digitizing techniques for scanning photographic plates. Several decades ago, he explains, investigators at the Lick Observatory spent ten years conducting a visual, microscopic inspection of photographs covering thousands of square degrees of sky; meticulously, they counted faint, marginally resolved galaxies, a few square arc minutes at a time. Their effort proved of immense value later, when other researchers studied the large-scale distribution of matter in the Universe and the distribution of absorbing material in our Galaxy. But the program was costly in terms of human effort.

Today, investigators at Carnegie's Observatories still conduct such surveys from photography. But now, instead of examining the plates by eye, they digitize them by a process of scanning microdensitometry; faint, small galaxies are detected by computer comparison of the shapes of all images with those produced by the "point sources" (i.e., stars). The technique is very fast, and it eliminates errors caused by fatigue and tedium. Meanwhile at DTM, investigators are applying like digital techniques to find, catalog, and measure fine structures in images of elliptical galaxies. Here too, the method is vastly superior in speed and precision to old photographic enhancement techniques.

Preston notes that the digital revolution brings its price. Both the 2D-Frutti and the direct CCD camera will make unprecedented demands on the computer in Pasadena. It is plain that their use will require planning to cope with the flood of new data; otherwise, Preston concludes, "we will drown in a sea of numbers."

Preparation for the Hubble Space Telescope

The launch of the Edwin P. Hubble Space Telescope awaits late 1986, but in many of their activities in this report year, Carnegie astronomers made preparations for its use. Jerome Kristian served as a member of the Investigative Definition Team for the Wide Field/Planetary Camera. Allan Sandage completed a NASA-sponsored catalog of resolved galaxies suitable for many studies in space (see page 64); several staff members participated in committee work of the Space Telescope Science Institute. DTM's Vera Rubin, for example, chaired the Working Group on Galaxies and Clusters of Galaxies, whose membership included Alan Dressler and Allan Sandage.

During the year, 26 nights at the 1-meter Swope telescope at Las Campanas were allocated to William Baum of Lowell Observatory for establishing photometric standard stars for use with the filter

set of the Wide Field/Planetary Camera. The project observer, Hugh Harris (Lowell Observatory), subsequently reported completion of "all important parts of the project."

During March 1985 at the Mount Wilson 2.5-meter telescope, Michael Shara (Space Telescope Science Institute) and colleagues investigated the frequency of binary stars among 250 candidate guide stars for the Space Telescope. The Telescope's guiding system will be unusable where two stars of a binary pair are too similar in magnitude and unsatisfactorily separated as seen on the sky.

Earlier estimates held that such binaries would occur in about 10% of cases; given that only three guide stars are to be programmed for each Space Telescope target, anything higher than 10% would create a significant problem. Preliminary analysis of the Mount Wilson data shows that the frequency is greater than 20%, so that changes in Space Telescope operational procedures or software appear to be needed.

The Formation of the Planets

> From the perspective of the origin of the Sun and the entire solar system, the formation of the terrestrial planets, including the Earth and its satellite, the Moon, is but a minor detail. Nevertheless, the manner in which the Earth formed is essential to defining its initial state, which in turn to a large extent determined its subsequent history.
>
> George W. Wetherill, Director
> Department of Terrestrial Magnetism
> July 1985

> The composition of planets ultimately can be traced back to the processes in the primordial solar nebula.
>
> Hatten S. Yoder, Jr., Director
> Geophysical Laboratory
> July 1985

About 4½ billion years ago, a small instability occurred in a region of our Milky Way Galaxy about 30,000 light years from Galaxy Center. The local material began to collapse gravitationally toward a common center of mass, and as the collapse proceeded the effects of the initial rotation became more and more important. Most of the mass eventually gathered at the center to form a single new star, and around this central star was formed a thin disk of gas and dust. Both the disk and the star rotated about the same, central axis, in the same direction. Several million years later, several planets and many smaller orbiting bodies were in place—formed of the gas and dust of the rotating disk.

These events are the large picture of the formation of our Sun and solar system, as it is generally understood.

Practitioners of several subdisciplines are turning their attention to various stages in this process, testing its validity and expanding understanding of its details. Experimentalists at the Geophysical Laboratory are studying materials under high-temperature and near-vacuum conditions, simulating those that may have existed in the "solar nebula." Investigators at DTM are using computer simulations to gain understanding of how an ensemble of smaller bodies may have accumulated to form the present inner planets. Other investigators, at the Geophysical Laboratory, in experiments at high pressures, are asking about the interiors and origins of gaseous, outer planets.

Experiments in Planetary Petrology at the Geophysical Laboratory. Reviewing work on the evolutionary processes of the solar system, Hatten Yoder notes that much has been learned from lunar and planetary missions, by observations from the Earth, and by experimental work with earth materials. Data of urgent interest include pressures, temperatures, and chemical compositions at different times and places in the evolving solar system.

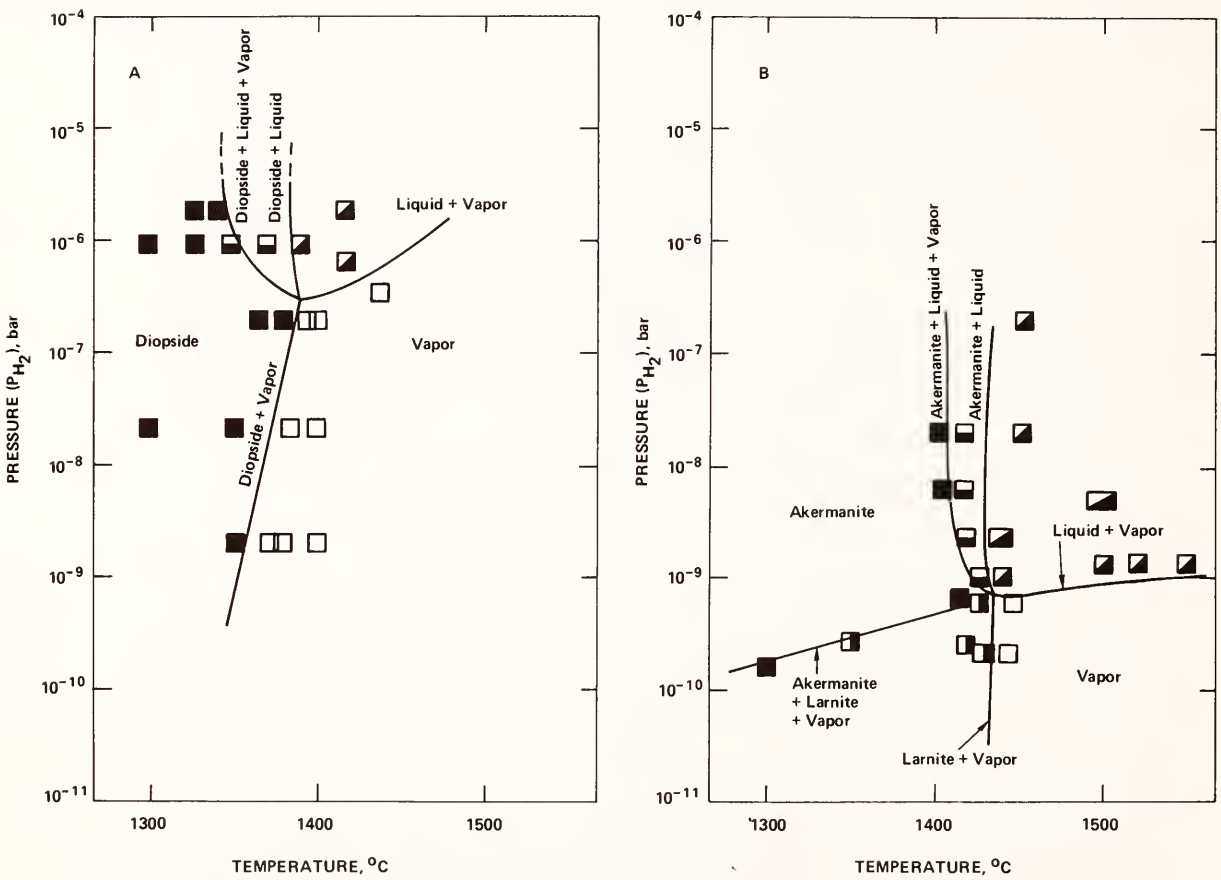
Yoder writes that theoretical calculations show that pressures and temperatures increased toward the center of the collapsing solar nebula. These pressure and temperature gradients, he continues, controlled the distribution of the elements in the solar nebula with a systematic increase in volatility (and decrease in density) with increasing distance from the center of the collapsing nebula. It is thus fundamental to determine the conditions in the solar nebula during the initial transition from the vapor state of the materials ultimately destined to form the planets and moons, as well as the physicochemical principles governing the evolution of these materials during condensation.

Certain materials found in meteorites, especially in the calcium-rich and aluminum-rich inclusions of carbonaceous chondrites, are believed to be representative of the oldest solar system material. These inclusions suggest that such typical terrestrial rock-forming minerals as pyroxene and melilite were important during early crystallization in the solar nebula. Important end members of the solid solutions in these mineral groups are diopside ($CaMgSi_2O_6$) and akermanite ($Ca_2MgSi_2O_7$).

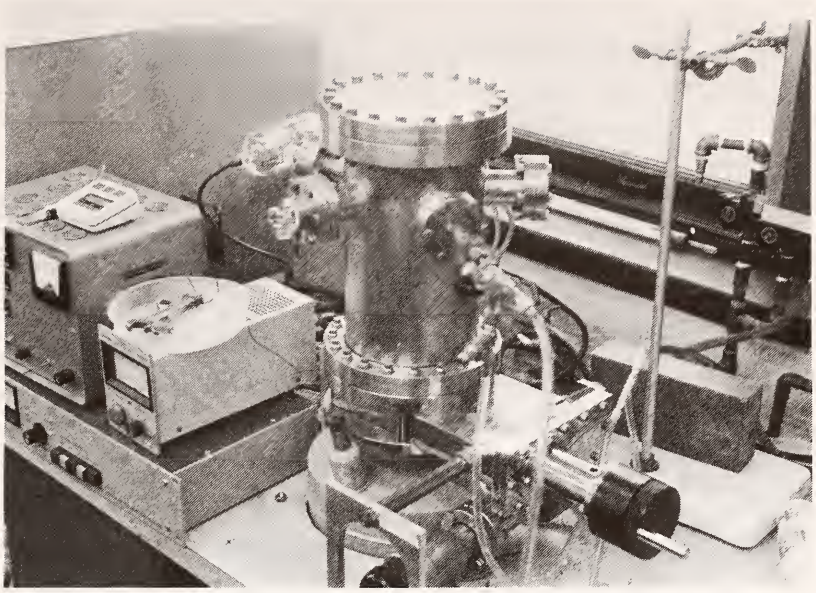
A basic point is how these minerals formed—whether by direct condensation from a gas or by crystallization from an intermediate liquid phase (partially or completely molten rock), or whether condensation indeed played an important role in the formation of the proto–solar system. Bjørn Mysen, David Virgo, and Ikuo Kushiro at the Geophysical Laboratory have conducted experiments with both materials to determine the pressure and temperature conditions under which these processes may have occurred.

They find that under no circumstance can diopside or akermanite precipitate directly from a gas at pressures above about 4 $\times$ 10^{-7} bars. Only a melt will condense. At conditions where vapor and melt are both present, there is a pronounced increase of Ca relative to Mg in the liquid phase. Upon further cooling at temperatures near 1500°C and pressures above ~10^{-7} bar, crystalline diopside and akermanite coexist with Ca-enriched liquid. The complexities of this process, which most likely took place as parts of the solar system evolved in this pressure-temperature region, are clearly large.

The experiments are also showing that under these low-pressure conditions the solidus temperature below which liquid does not exist for both minerals is lowered below that at 1 bar pressure. At sufficiently low pressure the crystalline silicates form directly



Results of the recent experiments at the Geophysical Laboratory at near-vacuum pressures approximating conditions in the early solar system. Experiments with (A) $CaMgSi_2O_6$ (diopside) and (B) $Ca_2MgSi_2O_7$ (akermanite) in hydrogen vapor. Symbols show state reached by the sample at the experimental conditions shown. (Open squares, vapor; diagonally divided squares, liquid; horizontally divided squares, crystal + liquid; vertically divided squares, larnite + vapor; solid squares, all crystalline diopside or akermanite.) Note that liquid diopside does not occur at pressures below about 10^{-7} bars. Above this pressure, chemical fractionation associated with the liquid state is an important aspect in understanding the formation of the solid material now composing the planets and moons of the solar system. Note the existence of the intermediate larnite material in vapor-akermanite transition.



The high-vacuum apparatus built at the Geophysical Laboratory for experiments at pressures and temperatures believed to exist during formation of the solar system. The assembly contains a small sample chamber and a heater unit. Hydrogen gas is bled in, and the desired conditions are maintained during the several hours of an experimental run.

from a gas; that pressure is about two orders of magnitude lower for akermanite than for diopside. The temperature for the vapor-crystal surface below 10^{-9} bars is nearly 100°C higher for akermanite than for diopside. Finally, whereas diopside evaporates directly to a gas phase without change in proportion of the components, with increasing temperature akermanite is first transformed to a mineral deficient in Mg and Si (larnite, Ca_2SiO_4) perhaps as much as 100°C below the final temperature of evaporation. Analytical data on residual materials sampled during the evaporation process in the laboratory are in accord with this inference. This last observation, predicted by theory but never confirmed experimentally, is consistent with strong fractionation of Mg (and to a lesser degree Si) into the vapor phase during condensation in the solar nebula.

Yoder comments that perhaps the most important conclusion to be drawn is that clinopyroxene and melilite minerals could have formed directly by condensation processes in the solar nebula only under very low pressure—less than about 10^{-7} bars. This conclusion is now reached on the basis of firm experimental work. Further, whereas traditional models of chemical processes in the solar nebula could not account for the widespread evidence indicating that melting processes were important, the new experimental data remove this obstacle. Because of positive pressure and temperature gradients toward the center of the nebula, it is likely that condensation into melt from the gas phase and subsequent crystallization of minerals from the melt were increasingly important toward the center of the nebula. This hypothesis, Yoder notes, leads to the suggestion that there must be

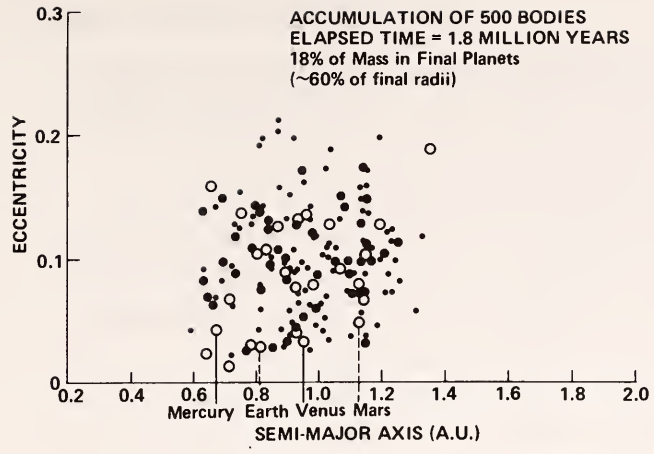
systematic chemical differences between the terrestrial planets as a function of their distance from the Sun.

Studies at DTM on the Accumulation of the Terrestrial Planets. Much of George Wetherill's research in recent years has been directed toward understanding how an ensemble of orbiting smaller bodies could have grown by accumulation into the present system of planets. Until recently, it was commonly assumed that four "embryos" of the present inner planets were formed early in solar system history, and that each then grew, largely independently of one another, by accumulating lesser bodies. Wetherill, however, in his computer simulations of planetary growth, has shown how a population of many smaller planetesimals whose total mass is roughly that of the present inner planets could grow through accumulation to reach a final configuration much like the present solar system. In his latest work, Wetherill started with a population of 500 planetesimals. (This improvement over his earlier 100-body simulations was made possible by the VAX 11-780 computer acquired by Carnegie several years ago.) Wetherill's new results show the likelihood that early planetary growth involved, not four main embryos, but an early population of many smaller bodies.

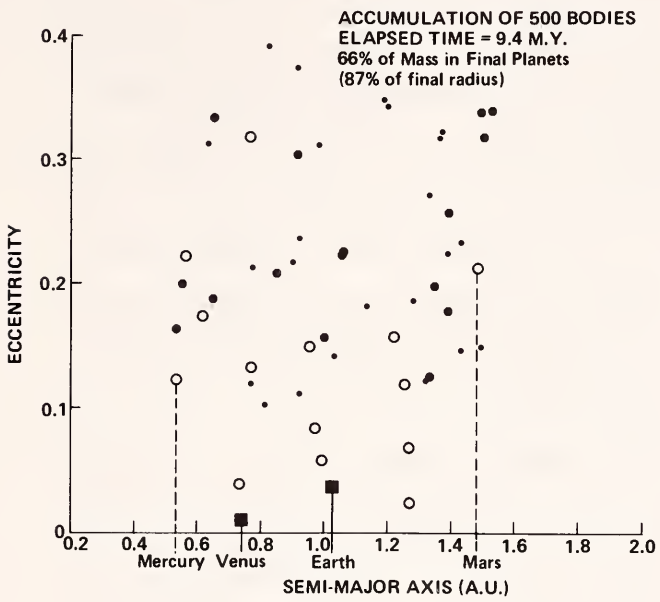
Further, he finds that in the late stages of accumulation, more than four main bodies were formed. Several of these then collided with one another to form the final planets seen today; bodies as large as present Mars and Mercury collided with the Earth and Venus during the late stages of growth. The strong mutual gravitational perturbations of these massive bodies caused their orbits to change drastically during growth. As a consequence, Wetherill believes, it is likely that the present planets interchanged their positions as they grew larger. This is particularly true for the more easily perturbed smaller planets, Mercury and Mars. It is possible that Mercury experienced much of its growth in orbits beyond the present orbit of the Earth.

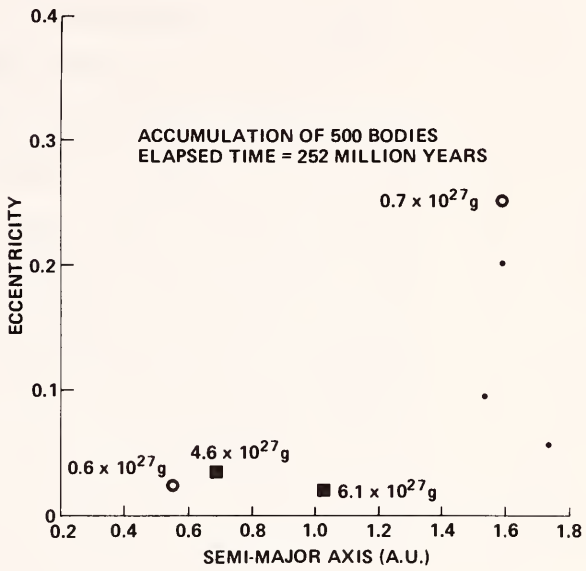
The impacts of these large bodies on one another very likely influenced profoundly their thermal, chemical, and geological evolution. The energy input associated with even a single major impact could have melted and chemically differentiated a large fraction of the Earth.

Such events may have been of special importance in the formation of the Moon, Wetherill notes. It has always been unclear how an object as large as the Moon could have acquired the angular (i.e., rotational) momentum needed to maintain its present orbit. Earlier calculations of planetary growth led to the result that the angular momentum contributions of the small accumulating bodies would nearly cancel one another, so that the resulting net angular momentum about each planet would be close to zero. This would probably not be the case if the input of angular momentum



In computer simulations exploring the accumulation of the inner planets, DTM's George Wetherill programmed a swarm of 500 planetesimals in elliptical orbits about the Sun. The above diagrams, representing one such simulation run, plot eccentricity (degree of ellipticity) against the semi-major axis (distance from Sun) for individual bodies after 1.8, 9.4, and 252 million years. The objects destined to become the four inner planets are indicated. At 252 million years, nearly all of the initial mass of the swarm is in the four principal bodies.





to the Earth-Moon system was dominated by a few, large events. Thus, new calculations by Wetherill provide support for the idea that the Moon may have been formed from the Earth as the result of a giant collision with a Mars-sized body. This hypothesis is now receiving serious theoretical treatment, and it is possible that the long-standing question of the origin of the Moon may soon have a plausible answer.

Like many important results in science, Wetherill's are in part an evolution from earlier discoveries by others. Last year, Hiroshi Mizuno and Alan Boss at DTM (*Year Book 83*, pp. 70–71) used numerical modeling to examine the phenomenon of "tidal disruption," which occurs when two bodies approach one another, within about three times the radius of the larger body. In such cases, the larger body exerts forces on the smaller, which if continued long enough, would fragment the smaller into many pieces. If this regularly occurred, all but the largest bodies would be destroyed, and the conclusion that planetary accumulation is characterized by collisions of bodies of comparable mass would be invalid.

Mizuno and Boss showed that it is quite unlikely that tidal dis-

ruption is frequent enough to lead to this result. They demonstrated, in agreement with the classical view, that if the smaller body was in close orbit about the larger and if the tidal forces had an indefinite time to operate, then tidal disruption would occur. In contrast, on the time scale of a "flyby" close encounter, these forces would be ineffectual. The only possible exception is an extremely close encounter of a previously melted body; it is likely that such circumstances are so rare as to be of only minor importance.

Wetherill's 500-body simulation took strength from the demonstration by Mizuno and Boss that tidal disruption is not a major factor; otherwise, a much larger starting population would have been required to achieve the same credibility of result.

Where Do Meteorites Come From? In yet another example of continuity in discovery, Wetherill has broadened his earlier work exploring the findings of Jack Wisdom, now at MIT. Wisdom showed that fragments produced by collisions among asteroids in the region 2.5 A.U. from the Sun can be perturbed into Earth-crossing orbits on a $\sim 10^6$-year time scale. (An Astronomical Unit, or A.U., is the average distance of Earth's orbit from the Sun.) Wetherill showed that this population of fragments fits the observational data for ordinary chondrites—the most abundant type of meteorite (*Year Book 83*, p. 69.)

Wetherill has now explored other regions of the asteroid belt as possible sources of less-common types of meteorites. His method is to determine the ratio of the fragment yield from alternative regions of the asteroid belt to that at 2.5 A.U. In this way, he avoids the difficult calculations of absolute meteorite yields—a calculation requiring uncertain extrapolation of laboratory hypervelocity data.

He finds that the second-most-important source region, at least for stony meteorites, is the innermost edge of the asteroid belt, between 2.17 and 2.25 A.U. The abundant low-inclination population of asteroids in this region will produce about 5–10% of the terrestrial flux of stony meteorites—in good agreement with the abundance of another important type of meteorite, the basaltic achondrites. Furthermore, the orbits predicted for meteorites from this region agree with those actually seen for this class, as indicated by the near-equality of afternoon and morning meteorite falls. (This contrasts with the ordinary chondrites from 2.50 A.U., which fall predominantly in the afternoon.) Wetherill finds other regions of the asteroid belt, including some regions to which significant meteorite production has been attributed, to be of minor significance as stony meteorite sources.

Thus it appears that major progress is being made toward understanding a basic problem of planetary science—identification of the sources of the meteorites, and development of a planetologi-

cal context for interpreting the record of the early solar system preserved in them.

Laboratory Investigations of the Outer Planets. Several investigations at the Geophysical Laboratory bear on the origins and compositions of the outer planets (Jupiter and beyond). Hatten Yoder writes that the outer planets formed from the condensation (and accretion) of more-volatile components of the solar nebula. The major components of the outer planets are hydrogen and helium; present in lesser amounts are water, ammonia, methane, nitrogen, and sulfur-bearing components. Knowledge of the equations of state (i.e., in part, their pressure vs. density relations) of these materials is important for determining the planetary internal structures. For example, the density distribution in the outer parts of Jupiter is consistent with the view that molecular hydrogen (H_2) is a major component. A distinction between a "crust" and "mantle" in Jupiter, at pressures between 1 and 2 Mbar, may be associated with phase transitions principally in hydrogen.

Accordingly, staff members Ho-kwang Mao and Peter Bell, with postdoctoral fellow Russell Hemley, are investigating experimentally the behavior of hydrogen at appropriate high pressures. Using the Laboratory's diamond-anvil, high-pressure apparatus, these investigators recorded the Raman spectra of solid, crystalline hydrogen under increasing static pressures up to about 1.5 Mbar, in order to characterize the interaction between the hydrogen atoms as a function of pressure. They observed a gradual change in vibrational properties beginning near 0.35 Mbar, which increased significantly above 1.0 Mbar. Although detailed structural interpretation of the results requires further study, the data are consistent with a crust-mantle boundary characterized by a transformation of essentially molecular hydrogen to a structural state with greatly weakened H-H interaction and, therefore, greatly different physical properties at pressures above about 1 Mbar.

In companion studies, the same investigators conducted experiments at high pressures with solid nitrogen and (in collaboration with research associate Ji-an Xu, predoctoral fellow Andrew Jephcoat, and Marvin Ross of the Lawrence Livermore Laboratory) with argon. These investigations provide fundamentally important information on the physics of gases at high pressure. Nitrogen and possibly argon are minor constituents of the planets; indeed, theoretical calculations suggesting that molecular nitrogen is transformed to a metallic state near 0.8 Mbar raise the geophysical implication that metallic nitrogen could exist in the deep mantle of the Earth. The current Raman spectroscopic and optical observations indicate, however, that this transformation occurs at static pressures above 1.5 Mbar. Thus, it is a very speculative possibility that metallic nitrogen could exist as a minor

component in the core of the Earth as well as in deep crustal portions of the outer planets.

The Restless Earth: Mantle, Plate, and Continent Interactions

The crucial roles of the rigid plates of the Earth's crust and mantle in shaping the Earth's geological processes became known to scientists some twenty years ago. The forces and motions of these plates, or "plate tectonics," became the center of a new synthesis of knowledge in the earth sciences, one that still gives focus to our understanding of the Earth and a frame for further research. The final synthesis was reached by scientists elsewhere, but Carnegie investigators at DTM and the Geophysical Laboratory made early contributions in developing the two necessary antecedents—the K/Ar isotope dating method, which provided the critical power of close discrimination among relatively young rocks, and an understanding of the Earth's magnetic reversals seen in rocks.

Since 1966, much of the leading inquiry in the earth sciences has been guided by attempts to comprehend the behavior of the lithospheric plates. Today, geochemists, seismologists, and experimental geophysicists are interested in how plate activity is related to the evolution and behavior of (1) the continents above and (2) the mantle below. Much of the work of Carnegie's earth scientists is therefore focused on related questions of continent-plate-mantle interaction.

Plate Subduction Processes. New oceanic plates are formed at the midocean ridges by the upwelling of mantle material; since the Earth's dimensions are not increasing, in some way an equal amount of material must be returning downward into the mantle. For the most part, this occurs at "subduction zones"—where ocean plates abut and move downward beneath the lighter material of continents. Subduction and its associated melting, metamorphism, volcanic and seismic activity, and tectonic processes in continental crust present difficult problems for earth scientists. But in these phenomena lie vital keys, both to the formation and evolution of the continental masses and to the structure and properties of the mantle beneath.

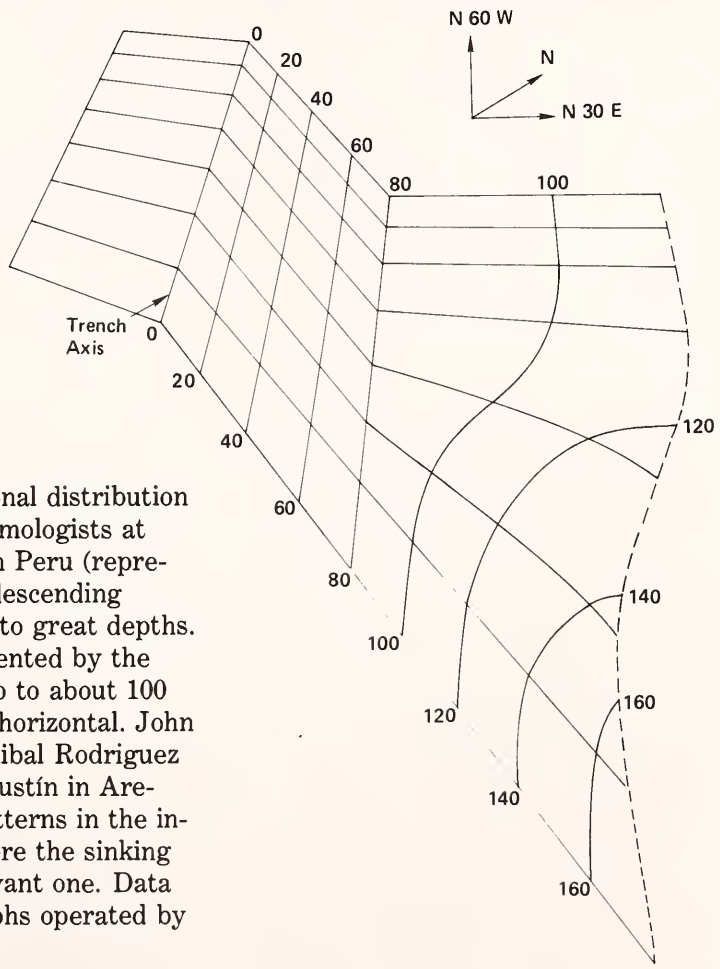
A subduction region of extreme interest lies in the western part of South America, including Peru. John Schneider and Selwyn Sacks of DTM, with colleague Anibal Rodriguez of Universidad Nacional San Agustín, are attempting to take advantage of the many earthquakes in the vicinity of the descending slab in an effort to characterize the exact shape of the slab and the tectonic stresses involved in its deformation. When the positions of these earthquakes are accurately determined by seismological techniques and plotted on a three-dimensional map of the region, the

earthquakes illuminate the slab structure, revealing its position much in the way that electric lights are used to show low flyers the position of the cables of a suspension bridge.

Two distinct mechanisms produce the earthquakes along the slab. At depths shallower than about 70 kilometers, earthquakes originate at the upper boundary of the slab from stresses generated at the boundary of the descending oceanic and overriding continental plates. The deeper earthquakes, however, originate within the descending slab itself. The source of the stresses causing the deeper earthquakes is poorly understood.

In moving toward a new interpretation of the stresses and behavior of the slab, Sacks and Akira Hasegawa (Tohoku University, Japan) several years ago used the three-dimensional distribution of earthquakes to map the position of the slab in central Peru, where the geometry of subduction is unusual. To the south of this region, the slab dips beneath the continent at an angle about thirty degrees from the horizontal—i.e., the subduction is essentially normal. In central Peru, however, after an initial dip to a depth of about 80 kilometers, the subducted plate appears to be buoyant and moves horizontally for several hundred kilometers before again plunging downward.

Between central Peru and the region of normal subduction lies a zone of contortion. Until recently, existing seismic data were insufficient to evaluate the extremely complex stresses in this zone.



By mapping the three-dimensional distribution of earthquakes in the region, seismologists at DTM determined that in southern Peru (represented by the lower curves) the descending oceanic slab is subducted steeply to great depths. In central Peru, however (represented by the upper curves), after the initial dip to about 100 kilometers, slab motion is nearly horizontal. John Schneider, Selwyn Sacks, and Anibal Rodriguez (Universidad Nacional de San Agustín in Arequipa) are studying the stress patterns in the intervening zone of contortion, where the sinking plate is tugging on the more buoyant one. Data are from a network of seismographs operated by the Universidad.

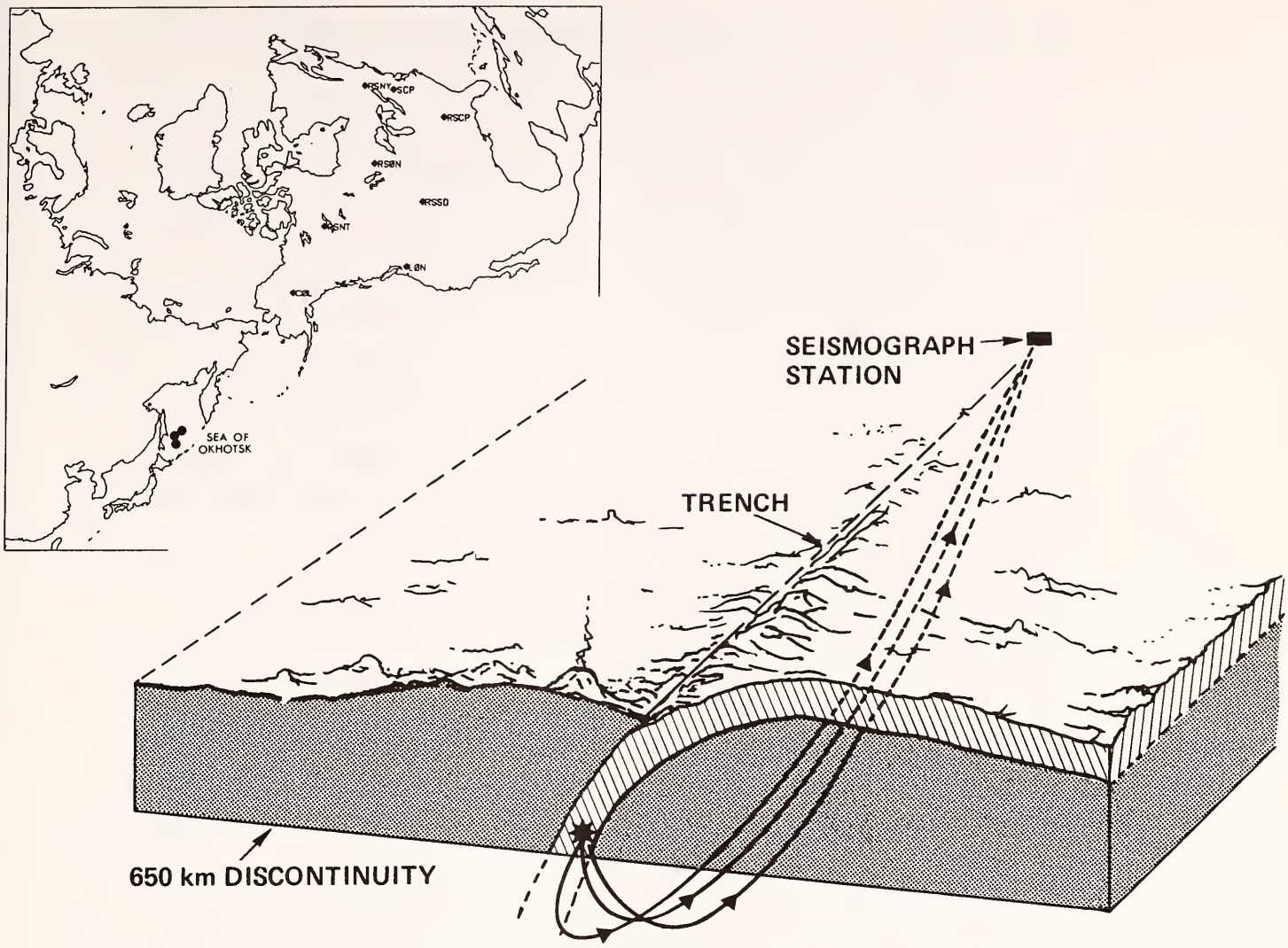
A local network of high-sensitivity seismographs operated by the Universidad Nacional de San Agustín in Arequipa has now provided ample data. Schneider, Sacks, and Rodriguez find that the stresses in the contorted zone are those expected from a model where the normally sinking plate is tugging on the more buoyant slab in central Peru, trying to pull it down into the mantle while the more buoyant slab resists these forces. The complex stress patterns in the zone of contortion appear to result from interplay of these opposing forces.

The observations support the idea that the principal source of the stress in all these regions is the same: in some way the slab is acting as a stress guide which causes the tensional forces to be parallel to the slab outside the contorted region. The weight of the slab itself is sufficient to explain the contorted motion of its subduction. Alternative hypotheses, which involve stresses that ultimately result from the distortion of the slab, are difficult to reconcile with the data and fail to provide a unified explanation of the stress distributions in all three—the normal, contorted, and buoyant—subduction regions.

How Deep Subduction? The issue whether subducted plates are confined to the upper mantle or whether they travel deeper, into the lower mantle, has remained a topic of intense controversy for more than a decade. Staff member Paul Silver and postdoctoral fellow Winston Chan at DTM recently found seismic evidence strongly suggesting that at least one plate—the Pacific plate under the Sea of Okhotsk—descends into the lower mantle. Silver and Chan examined seismograms from several very deep earthquakes (about 600 km deep) from this region recorded at North American stations of the Global Digital Seismic Network. They found that many of the shear waves consist of two and sometimes three pulses, rather than a single arrival. When seen elsewhere, this phenomenon, called multipathing, is usually the result of abrupt changes in seismic velocity along the path of the wave travel.

The investigators considered several possible causes for the extra pulses: a flat-lying discontinuity beneath the receiving stations (such as the Moho), a deeper discontinuity in the lower mantle, or some form of heterogeneity near the earthquakes. By various arguments Silver and Chan ruled out all but the third possibility, and they deemed that a possible explanation lay in the presence of subducted slabs in the regions where the earthquakes occurred. Since the slabs would have descended into a relatively hot mantle, the slabs would be colder and therefore have higher seismic velocities than the ambient mantle. The multiple pulse arrivals thus could be produced by refractions from this high-seismic-velocity material.

To test the idea, Silver and Chan conducted a series of numerical simulations, examining the effect of a high-velocity slab on the shear waves leaving the earthquake region. They found that strong refractions would indeed be expected in signals arriving at



A schematic cross-section illustrating the paths taken by waves produced by deep earthquakes beneath the Sea of Okhotsk. Staff member Paul Silver and postdoctoral fellow Winston Chan at DTM demonstrate that the seismic signals originating at the subducted slab are refracted in the lower mantle; multipathing is seen in the signals received at the seismograph stations in North America, shown in the adjacent map. The result is evidence supporting the existence of deep subduction.

the stations used in the study. Significantly, since the earthquakes are very deep and since the waves observed start downward from the earthquake source, the places where the waves "bounce" off the slab must be in the lower mantle—at least several hundred kilometers beneath the 650-km discontinuity. Thus, the results provide evidence that the subducted slabs indeed penetrate this important barrier. (See figure, above.)

New Insights from Older Data. Leonidas Ocola of Instituto Geofísico del Peru, L. Thomas Aldrich of DTM, and J. H. Luetgert of the U.S. Geological Survey have recently analyzed past seismic data, using modern ray-tracing and other techniques. The investigators sought to develop a reasonable picture of the seismic velocity structure of the crust and upper mantle beneath the ancient Arequipa Massif in Peru. The data was originally ob-

tained by the DTM staff, collaborating with South American and North American colleagues in 1957, 1968, 1972, and 1976.

The chief elements of the new interpretation are that (1) in the region where the Nazca ridge intersects the continent—the region of horizontal subduction studied by Schneider, Sacks, and Rodriguez—refracting interfaces in the crust are shallower than elsewhere, suggesting that the ridge under the continent provides a buoyant effect, (2) the suite of seismic velocities from Lima southward to the Peru-Chile border is consistent with suites found in other very old terrains, (3) vertical blocks of slow seismic velocity lie near and to the southwest of the intersection of the continent and the Nazca ridge, and (4) while the refracting interfaces dip smoothly under the Arequipa Massif, the structure changes dramatically toward the northeast into the high plateau of central Peru, both in the velocities found and in their dip.

Meanwhile, measurements of the geomagnetic field at a network of stations in the Andean countries continue to provide a wealth of raw data for identifying electrical conductivity structures at depth within the Earth. Variations in components of the magnetic field are analyzed to deduce the subsurface currents that would produce the observed relationships. Presently at DTM, Aldrich and G. Z. Qi (on leave from the Institute of Geophysics, State Seismological Bureau, Beijing) have a twofold goal: to study the conductivity structure of the Andean region as a property in itself, and, when possible, to correlate the conductivity structure with other features of the region identified from seismic or geochemical information. They have shown, for example, that the conductivity structure in Peru, Bolivia, and northern Chile is quite different from that in central Chile—a result suggestive of the recent seismic results.

Qi and Aldrich have made an intensive comparison of possible methods for analyzing the magnetic data of the past twenty years. From studies using real data, they have concluded that a Butterworth-filtering technique allows them to select the most suitable part of a time series in each frequency band for measuring each component of the magnetic field. In addition, they are adapting the numerical-modeling techniques of T. R. Madden of MIT to the DTM computational facilities, toward the development of a modeling program for explaining the Butterworth-filtered data and exploring the geophysical ramifications.

The collection of past seismic and magnetic data from the Andes offers a rich resource for use in up-to-date frontier research. Aldrich, who spent many years at the Andes stations, and his colleagues are reaping benefits from past DTM initiatives in a region of extreme scientific interest.

Continent Formation: Geochemical Evidence from Mantle-Derived Rocks. Earth scientists are something like historians.

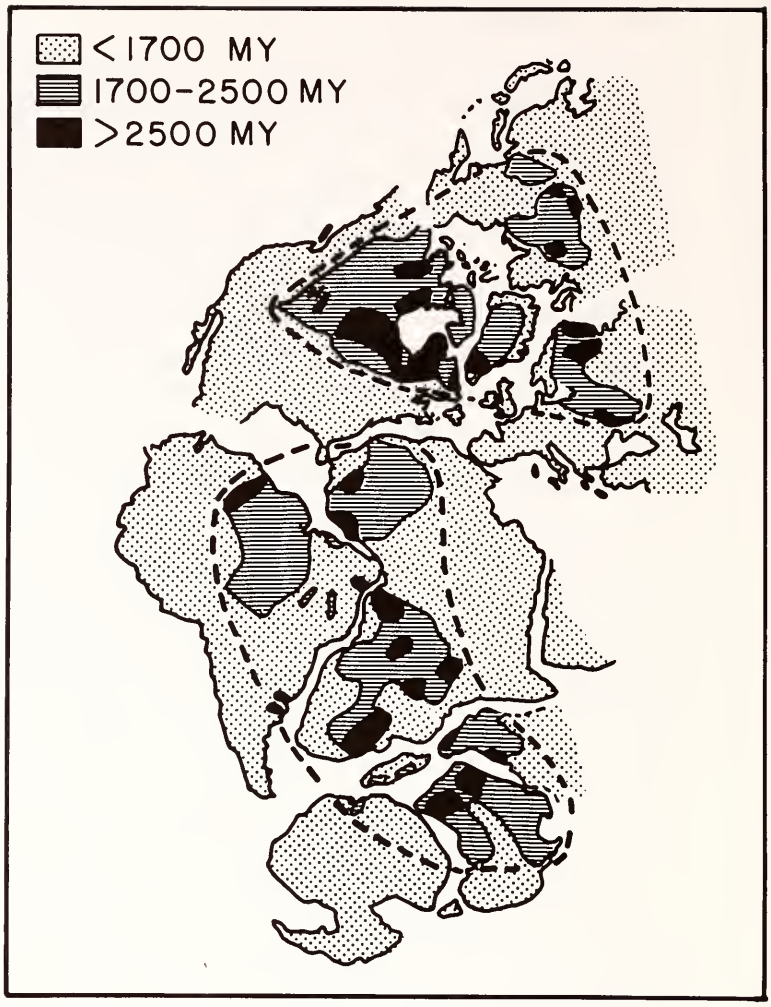
Their goal of understanding the present state of the Earth requires learning how the Earth has evolved from its initial state, to include the physics and chemistry of the processes responsible for that evolution. A history book without dates or chronology would be a mere collection of unrelatable events. Until a few decades ago, this resembled the condition for that large part of earth history known as the Precambrian. The basis for geological chronology was largely limited to the fossil record in rocks since the Cambrian—i.e., for the last 600 million years. For the Earth's first 3.9 billion years, scientists were forced to treat obviously unrelated local rock units simply as products of a poorly subdivided "Precambrian time."

During the last thirty years, new methods of measuring geological time have been developed, in large part owing to work by scientists at DTM and the Geophysical Laboratory. Ages can be measured using small rock and mineral samples, even though they may contain extremely small amounts of the naturally radioactive elements rubidium, uranium, thorium, potassium, and samarium. Thus it is now possible to date geological events as far back in time as rocks have been preserved.

As dating of earth materials became more widespread, interesting patterns emerged. Precambrian rocks, it developed, were not randomly distributed by age throughout the Earth. The most ancient rocks—those older than about 2.5 billion years—were found to cluster in particular regions, which in some cases corresponded to regions previously delineated on the basis of tectonic or lithological evidence. The younger Precambrian rocks—from 0.6 to 2.5 billion years in age—tended to surround the regions of very old rocks. The clustering by age was further emphasized when scientists reconstructed the locations of the continents prior to their last major breakup; the clustering was especially evident in the adjacent portions of North America, Greenland, Europe, and Asia. Later, the oldest known rocks—from 3.5 to 3.8 billion years in age—were found in parts of the older regions.

The emerging pattern suggested the hypothesis that those regions of rocks older than 2.5 billion years, termed cratons, were the sites of formation of the first continental crust early in earth history. A major research goal of the isotope geochemistry group at DTM is to understand the processes whereby these "continental cores" first formed from the mantle and then grew, and the relationship of these past processes to those occurring today. Equally challenging is to understand the nature of the continental mantle underlying the continental crust, and the extent whereby this continental mantle is as much a permanent part of the continental land mass as the ancient crust observed at the surface.

In a detailed isotopic and geochemical study of the igneous rocks of the largest of these cratons, the Superior Province of Canada, DTM's Steven Shirey recently demonstrated that one major compo-



Positions of the continents prior to the most recent major breakup about 200 million years ago. Clustering of material by age is evident: regions of the oldest rocks are generally surrounded by regions of intermediate age. The oldest regions (surrounded by dashes) are believed to be the original continental cores (cratons); how they formed from the mantle is a focal question among the geochemists at DTM. (After Hurley, P. M., and J. R. Rand, Pre-drift continental nuclei, *Science 164*, 1229–1242, 1969, and Burchfiel, B. C., The continental crust, *Scientific American 249*, 130–145, 1983.)

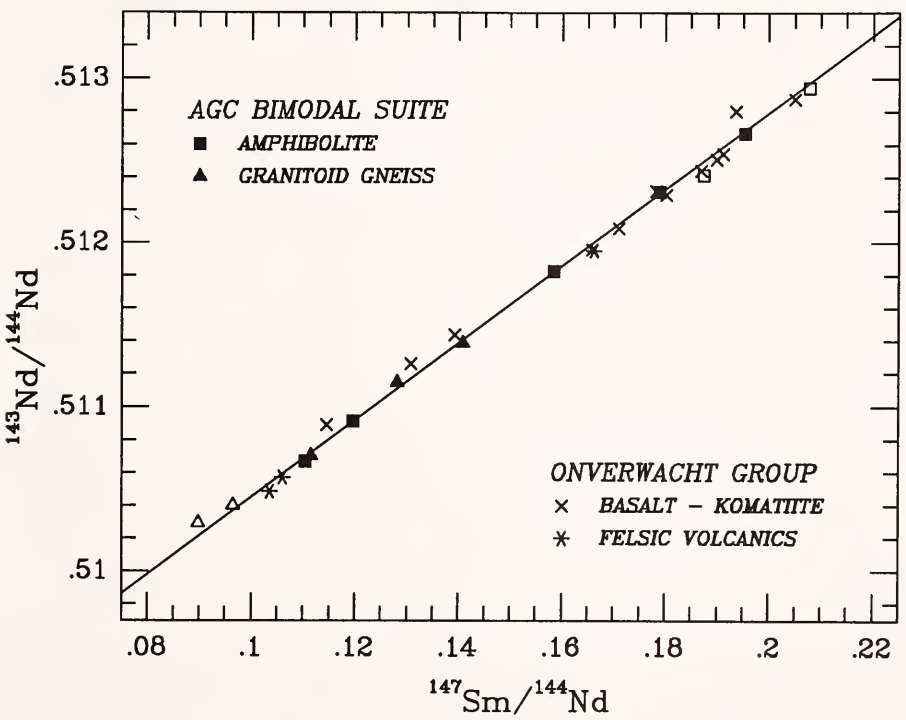
nent of the 2.7-billion-year-old crustal section—the Mg- and Fe-rich basaltic-to-komatiitic volcanic rocks—was derived directly from partial melting of mantle materials having only a limited amount of isotopic heterogeneity. In its degree of heterogeneity as well as in various other geochemical and isotopic characteristics, this mantle source may be similar to that supplying modern-day basaltic volcanism along the worldwide system of ocean ridges.

The second major igneous rock composing the Superior Province appears to have been derived from a mantle source enriched in incompatible elements and melted under different conditions of pressure or volatile content. Throughout the world, this rock type characterizes continental crust—a feature that distinguishes the latter from the purely basaltic crust of the ocean basins. Shirey argues that most of this "granitic" component also was derived by melting of the mantle, or at least by fractionation of Si-rich direct partial melts of the mantle. Shirey suggests that the mantle sources of these 2.7-billion-year-old rocks of the Superior Province were formed by a process of mantle enrichment, where incompatible-element-enriched fluids or melts were added to mantle sources originally similar to those of the basaltic-to-komatiitic rocks discussed just above. From Nd isotopic data, Shirey has shown that this mantle enrichment event occurred not more than 100 million years before the first episodes of crustal growth in the Superior Province.

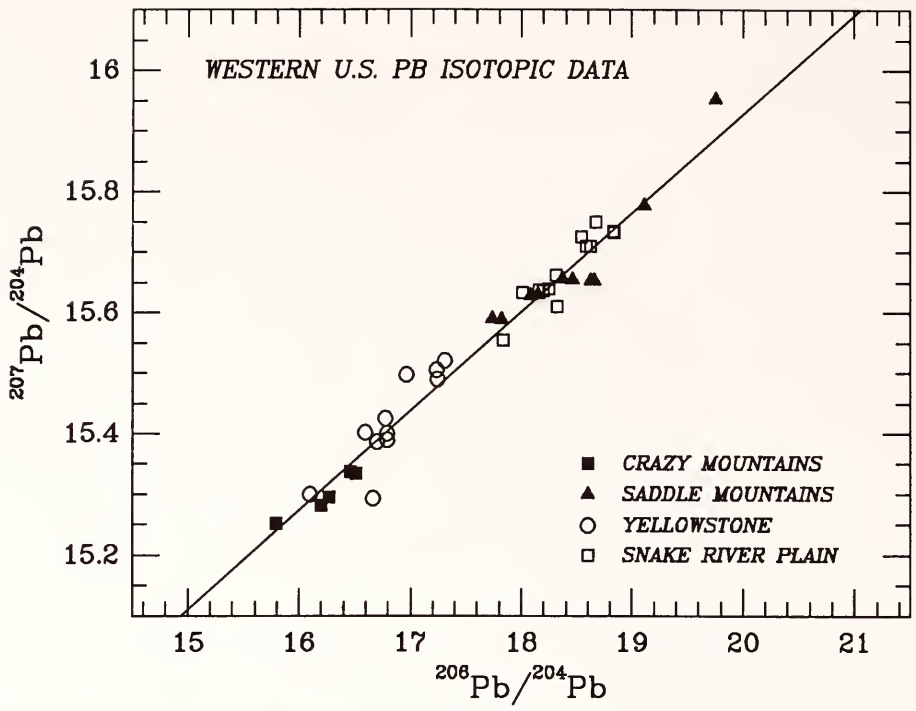
This concept—that the initial stages of cratonic growth occur over a short time interval (less than 100 million years) in association with mantle melting and enrichment events—is supported by the study of the oldest rocks of the Kaapvaal craton of southern Africa by DTM staff member Richard Carlson.

Carlson showed that the mixed basaltic and more "granitic" components of the highly metamorphosed Ngwane gneiss of Swaziland have exactly the same initial Nd isotopic characteristics as the basaltic-komatiitic volcanic rocks of the nearby Onverwacht Group. When combined on the same isochron diagram both the data for the Ngwane gneiss and Onverwacht volcanic rocks plot along the same 3.54-billion-year isochron, thereby indicating generation from a common mantle source over a period not exceeding 50 million years.

The Kaapvaal has long interested Geophysical Laboratory staff member Francis R. Boyd, who is now developing a theory for the formation of peridotite xenoliths—rocks erupted to the surface in kimberlite pipes and believed to have originated in the upper mantle. Boyd seeks to distinguish the origins of the xenoliths—whether they came from the lithosphere or from the higher-temperature asthenosphere below, or whether they formed closer to the surface by metamorphism and metasomatism in regions surrounding kimberlite magma chambers.



This plot supports the concept of a major enriching event which enhanced production of Si-rich rocks in the mantle. The isotopic data were obtained by DTM staff member Richard Carlson in rocks of the Ngwane gneiss and Onverwacht Group in Africa. Data from samples at both places, plotted above, fall along the same isochron, thereby indicating their generation from a common mantle source during a period of 50 million years or less.



Data obtained by Francis Dudás, Richard Carlson, and William Hart of DTM from selected young rocks of the western United States reveals co-linearity in their Pb isotopic compositions, as plotted here. All samples thus appear to derive from the same enriched mantle source underlying much of Washington, Idaho, and Montana. The result further strengthens the idea that a zone of ancient, enriched mantle underlies each continental craton.

Further understanding of mantle enrichment processes comes from the study by DTM predoctoral fellow Francis Dudás of igneous rocks from the Crazy Mountains of Montana. Although the rocks are only about 50 million years old, their Nd and Pb isotopic characteristics reveal that their mantle source was enriched in incompatible elements some 2.5 billion years ago, perhaps during the same event that created the Superior Province craton. The information provided by Dudás, coupled with that found by Carlson and former DTM fellow William Hart in a study of young basaltic rocks from Oregon, Washington, and Idaho (see *Year Book 81*, *82*, *83*), permits mapping a zone of 2.5-billion-year-old enriched mantle beneath the northern United States extending as far west as Washington. Thus the view strengthens, that a zone of ancient incompatible-element-enriched mantle underlies each major continental craton, and is isolated there from mixing with the underlying convecting mantle for periods of billions of years.

Mantle Enrichment by Subduction. Other work by Carlson and Hart on certain young basaltic rocks from the western United States shows that the mantle sources of these rocks were enriched by the addition of material derived from oceanic sediments carried down relatively recently with subducted plates. Evidence for the same phenomenon—recent mantle enrichment by sediment recycling—is seen even more clearly by DTM postdoctoral fellow Julie Morris in her combined Nd, Sr, and Pb isotopic and

trace element study of volcanic rocks related to the Banda subduction zone, Indonesia. Working with these very young rocks, Morris demonstrates not only that recently subducted sediments have affected the mantle sources of these lavas, but that the nature of this mantle contamination depends on the particular geometric and tectonic conditions influencing the source and quantity of the material being subducted.

For several years, Louis Brown, Fouad Tera, and colleagues at DTM and the University of Pennsylvania have worked to develop methods for measuring the isotope ^{10}Be in samples of earth material, using the tandem Van de Graaff accelerator at the University as a mass spectrometer. (See *Year Book 83*, pp. 79–81.) A focus of effort has been to measure ^{10}Be in various volcanic materials, in an attempt to trace how ^{10}Be collected in sedimentary ocean material is carried downward at trenches by subducting oceanic plates, eventually to reappear in the magma produced in the subduction-zone volcanos. The presence of high ^{10}Be concentrations in the volcanic materials would confirm that the overriding sediments and the plates themselves participated in the subduction. On the other hand, other surface materials—igneous rock of the mantle, midocean rises, rift volcanos, hot-spot volcanos, and ocean-island volcanos—should have very little ^{10}Be, always less than 10^6 atoms per gram (as opposed to more than 10^9 atoms per gram in ocean sediments).

During the first years of the project, the group sought to develop the necessary experimental techniques, confirm that the observed concentrations were not results of laboratory or sample contamination, and assess the range of concentration in various materials. In a recent paper, Tera *et al.* reported ^{10}Be concentrations in 106 arc lavas (where subduction is taking place) and in 33 flood basalt and other non-arc samples. Some of the arc lavas, as expected, exhibited high concentrations of ^{10}Be. But the investigators were surprised to discover great variation among arc lavas. The Aleutian and Central American samples have much-higher concentrations than the non-arc control group, but samples from three arcs—the Mariana, Halmahera, and Sunda—are indistinguishable in ^{10}Be content from the non-arc controls. This year, members of the group noted a possible explanation.

In the sea off southern California, the investigators noticed ^{10}Be deposition on the ocean floor ten times that attributable to atmospheric ^{10}Be in rainfall, a rate previously assumed to apply uniformly to the ocean. They explain the observation by noting that when an ocean current, in this case the California Current, encounters continental runoff, the runoff ^{10}Be is scavenged, thereby raising the overall ^{10}Be deposition rate and its concentration in local ocean-floor sediments. Such mechanisms may well be widespread near land masses and produce greatly different inventories of ^{10}Be, depending on the currents and the continental runoff. The

investigators note that the arc with the highest ^{10}Be lava concentration (Central America) also has the highest offshore sedimentation rate, while the arc with the lowest ^{10}Be lava concentration (Mariana) has the lowest sedimentation rate.

Thus, ^{10}Be inventories must be determined well outboard of coastal trenches, in measurements taken at various depths in deep-sea cores. Without such measurements, ^{10}Be values are reached only by speculation on the basis of sedimentation rates.

One structural feature of the Central American arc bears on interpretation of the ^{10}Be data. When the Central American volcanos formed, they punctured an older sedimentary layer of uncertain age, on the order of a few million years. It is possible that the ascending magma has mixed with these sediments in a chamber, so that the ^{10}Be has been derived from these local sediments rather than from ocean plate subduction. Some lava samples from the Central American volcanos Pacaya and Cerro Negro, for example, contain what could be pieces of unmelted sediment presumably carried to the surface more or less intact by the lava. Measurements by Brown *et al.* of ^{10}Be concentrations in two such samples argue against this possibility, as the ^{10}Be values are too low.

Julie Morris looked at the long-standing question, whether the ^{10}Be concentrations of the volcanic samples have been altered after their arrival at the surface by exposure to ^{10}Be-carrying rainfall. Morris examined by microscope a large number of thin rock sections taken from the volcanic samples. She determined the degree of sample alteration by water, and attempted to find correlation between such alteration and the ^{10}Be concentration. She found no correlation—a result arguing against rainfall as a major source of ^{10}Be in the samples. In addition, she determined that the volumes of pure rainwater needed to produce the petrologic alterations observed could not have been large enough to produce the observed ^{10}Be concentrations.

DTM's Nathalie Valette-Silver and colleagues this year demonstrated yet another use for ^{10}Be measurements. They have measured ^{10}Be concentrations in sediments of various drainage basins in the eastern United States, and made comparisons with the amounts incident on the basins in rainfall. Their results indicate that surface erosion in the Piedmont, landward of the fall line, is greater than the past long-term average, perhaps because of destructive farming from about 1750 to 1925. Readings in the Coastal Plain and in the Highlands generally indicated steady-state erosion. The ^{10}Be method avoids the need to rely on imperfect measurements of sediment concentrations in streams and on imperfect values of average sediment transport; it promises to be useful for studying the rate at which continents are being eroded.

Theoretical Approaches to the Active Mantle. The movement of

heat and material by convection through the mantle has long been accepted among earth scientists, and there is general agreement that in some way, zones of rising convection in the mantle are somehow linked to such surface manifestations as the upwelling of heated material at the midocean ridges and, perhaps, at persistent hot spots. But beyond this, questions as basic as whether cells of convection reach from the foot of the mantle all the way to its top, or whether there are two or more distinct layers of convection, remain unanswered.

DTM staff members Alan Boss and Selwyn Sacks recently improved their models of time-dependent convection in the mantle. Because of insufficient resolution, they had been unable to verify that the initial, transient period of multiple-layer convection shown in their earlier models (*Year Book 83*, p. 72) was not a numerical artifact. To double the spatial resolution in the numerical code (originally developed by Richard Lux at DTM), a 32-fold increase in computer time would have been required, a circumstance ruling out use of the Institution's VAX computers.

The problem was overcome by full-time use of the FPS-100 array processor, a high-speed specialized computer, attached to the VAX 11/780. In this way, Boss and Sacks have calculated ten new models which conclusively demonstrate agreement with their earlier results.

Meanwhile, Boss is in the process of developing a new computer code for studying mantle convection, one that will be much more efficient than the Lux code in calculating present-day convection as well as the supposedly more vigorous convection of the early Earth. The new code will avoid many of the approximations that have limited the applicability of current models of mantle convection, relaxing the Boussinesq approximation and considering the fully compressible, self-gravitating, two- and three-dimensional flow of a spherical mantle. The new code will also allow material properties such as thermal conductivity and viscosity to have arbitrary dependence on pressure, temperature, and other variables, subject only to spherical symmetry in the viscosity field. Results of laboratory experiments, along with seismic and geochemical evidence, can thus be introduced with known relations in thermodynamics, fluid mechanics, and petrology to provide closer insights into the mantle's history.

PASSCAL: A Major Venture in Seismology. Much of our knowledge of the inner Earth has come from study of seismic vibrations, or waves, generated by earthquakes or explosions, and their travel through the Earth. Until now, however, the resolution possible with recorded seismic data in general did not allow examination of particular, local subsurface features. Thus our knowledge of the behavior of the lithospheric plates, for example, or of particular regions of the upper mantle, is often vague.

PASSCAL—the Program for Array Seismic Studies of the Continental Lithosphere—has been established as a major long-range research initiative within the National Science Foundation. A principal objective is to conduct high-resolution seismic studies of the continental lithosphere and beneath, using at least 1000, matched portable digital seismographs (*Year Book 83*, pp. 100–101).

The venture is by far the largest and most ambitious scientific initiative ever undertaken by the seismological community. Carnegie Institution provided early seed money, and to date DTM has acted as the lead institution for funding by NSF. Staff members David James and Selwyn Sacks have been named the principal investigators, and James has held the responsibility of administering funds. Their efforts have focused on the publication and worldwide distribution of the PASSCAL Program Plan, and the coordination of the instrumentation development program (to which most of the funds have been committed). The development of system architecture and instrument specifications are well on the way to completion, and instruments should be available for field experiments by 1987.

PASSCAL is one of two major seismological programs joined under Incorporated Research Institutions for Seismology (IRIS), a nonprofit corporation representing 48 academic institutions. (The other major program of IRIS is the 100-station global digital seismic network.) Beginning in fiscal year 1986, PASSCAL funding will be through IRIS, which has a new president, staff, and office. The Carnegie role as lead institution will end at that time.

A new objective will then dominate—to develop the analytical methods and data-processing techniques needed to exploit the new kinds of seismic data, which will be available massively from both PASSCAL and the global seismic network. The challenge will be great, for digital data require tools very different from those of the past.

James, Silver, Sacks, Schneider, Chan, and postdoctoral fellow Timothy Clarke have been working to develop such tools, and to gain practical experience in using them. In collaboration with Robert Meyer of the University of Wisconsin, James and Clarke have been processing and analyzing data obtained with the University's "triggered" portable digital seismic instruments, which are among the few now available in the academic community.

The earthquake of October 28, 1983, at Borah Peak, Idaho (magnitude 7.3), produced several thousand aftershocks in a region trending north-northwest, 75 km long and 15 km deep. Nine Wisconsin seismographs were installed in a 10 × 10 km array in the region, and recordings were obtained over an eight-day period. Of more than 2000 events recorded, the investigators are using about 500 in their analysis. About 600 megabytes of total digital data are involved, and while this quantity is small

in terms of expected PASSCAL data sets, it should amply demonstrate the power of digital seismology. The analysis will use the seismic data to determine the location in the crust of the aftershocks and the seismic velocity structure of the upper crust. The earthquake data can then be processed as if they were explosion data, using sophisticated methods of data analysis similar to those used for conventional reflection seismology. The analysis should result in seismic images of deep crustal (and possibly upper mantle) reflectors in the Earth below the zone of earthquakes (i.e., at depths exceeding 5–15 km) for the general region.

Experimental Studies on Crust and Upper Mantle Processes

> Advances in the investigation of earth processes are perceived to be dependent on the invention of new devices for controlling the important variables. Such devices and techniques account for the apparent sudden spurts of advancement in the extension or precision of measurement, whereas advancement of ideas of lasting value requires more extended time for development and assimilation.
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> Hatten S. Yoder, Jr., Director
> Geophysical Laboratory
> July 1985

Many processes in the evolution of the Earth and terrestrial planets are attributable to mass and energy transfers, governed by the fundamental laws of physics and chemistry. Such transfers may result from interaction between crystalline materials (i.e., rocks), partially molten rocks (magma or magmatic liquids), and fluids (typically combinations of common components such as water and carbon dioxide). In such events as the formation of oceanic and continental crust, volcanic activity, and element enrichment in crustal rocks, the principal transfer processes are understandable only in terms of the chemical equilibria between minerals, melts, and fluids, and the physical properties of magma, such as density, viscosity, and conductivity. Much of the research at the Geophysical Laboratory focuses on the development of a general physicochemical basis for characterizing these phenomena.

Silicate Liquids: How Structure Relates to Property. The macroscopic properties of natural materials reflect the microscopic properties, or structures, at the atomic and molecular levels. It is, therefore, necessary to determine mineral, melt, and fluid structures by laboratory measurements and theoretical calculations, and then to relate this structural information to the macroscopic properties. Research by staff members Bjørn Mysen, David Virgo, and their associates during the last seven years has resulted in a general model of the structure of magmatic liquids and in the iden-

tification of many of the principal relationships that exist between structure and properties of magmatic liquids.

Briefly, they have established that the structure of magmatic liquids can be described as consisting of many interconnected tetrahedra each having a silicon cation in the center and atoms of oxygen in the four corners (the SiO_4^{4-} units). Individual tetrahedra are connected with others by sharing oxygens ("bridging oxygens") to form chemically more complex units, such as $Si_2O_7^{6-}$ (one shared oxygen per silicon), SiO_3^{2-} (two shared oxygens per silicon to form infinitely long chains or rings), $Si_2O_5^{2-}$ (three shared oxygens per silicon to form planar structures), or SiO_2 units (where all four oxygens in each tetrahedron are shared by neighboring tetrahedra). In those resulting structural units where fewer than four oxygens are connected to a neighboring Si, these *nonbridging* oxygens act as links to other structural units through bonding with non-Si cations. Each of these cations are bonded to six or more such oxygens. In natural magmatic liquids, these units occur in varying proportions, which are systematic functions of temperature, pressure, and bulk composition.

A major focus of the current research is to determine thermodynamic and physical properties of magmatic liquids within the framework of the established structural information. The properties are related to the strength of the silicon-oxygen and the metal-oxygen bonds. Diffusion, viscous flow, and other transport properties of silicate liquids can be described quantitatively in terms of the disruption and formation of such bonds.

For example, the configurational changes in a melt with changes in temperature, pressure, and composition have been theoretically related to the proportions of the different structural units in the melts. These relationships have been studied by Mysen, Virgo, visiting investigator Christopher Scarfe (University of Alberta), and David Cronin (National Bureau of Standards) in a project that included measurement of melt structure and determination of the viscosity of the melts. The investigators succeeded in observing the expected relations, and they produced the first quantitative measure of the changes in activation energy of viscous flow as a function of observed structural changes.

The above study by Mysen and colleagues was designed to evaluate the principles of a model for use in calculating viscosity of magmatic liquids. The melt compositions used were simplifications of natural melts. Aluminum is important because it is a major element in most natural materials, where Al^{3+} may substitute for Si^{4+} in the silicon-oxygen tetrahedra. Observations from crystal chemistry of aluminosilicate minerals show that Al^{3+} exhibits distinct preferences for crystallographic sites. In aluminosilicate melts where the number of available "sites" is greater because of the coexistence of different types of structural units, a distinct partitioning of Al^{3+} between different units might be suggested.

Mysen, Virgo, and Friedrich Seifert (University of Kiel) investigated predictions of such partitioning in silicate melts, and found that substitution of Al^{3+} for Si^{4+} in the tetrahedra indeed governs the makeup of the structural units. The investigators thus predicted major changes in liquidus phase equilibria and also the viscous behavior of the melt with changes in the ratio of aluminum to silicon in the liquid.

In a companion study, postdoctoral fellow Donald Dingwell investigated the relationships of those data to viscous flow in aluminosilicate melts. He concluded that, for aluminous systems, it is necessary to modify the simple mixing model used to calculate configurational entropy of simple silicate systems. He observed two different effects. (1) In melts with low Al^{3+} content, the viscosity is primarily a systematic function of the proportion of aluminum to silicon in three-dimensional, interconnected oxygen tetrahedra. Because of the decreasing bond energies in such structures with increasing aluminum content, Dingwell observed the decrease in viscosity predicted from the melt structural information. (2) When the aluminum content is further increased, the viscosity increases, in contradiction to the generally accepted theory for viscous flow of silicate melts. The accepted theory, however, does not take into account the observation of Mysen, Virgo, and Seifert that because of the partitioning of Al^{3+} among the structural units in aluminosilicate melts, the concentration of the structural units wherein the Al^{3+} resides increases in a predictive way. Dingwell was able to interpret the viscosity data on this basis.

Mysen and Virgo's general model of magmatic liquid structure provides a frame for describing thermodynamic properties of magmatic liquids and coexisting crystals—needed for understanding the geochemistry of partial melting in the Earth's upper mantle, both during ascent of the liquid toward the surface and during final crystallization to form rock. Virgo and Mysen are the first to use laboratory determinations of phase equilibria in chemical systems with known crystal and melt structure in this way. Application of this method to chemically more complex natural systems, if feasible, should greatly simplify the theoretical treatment of the geochemistry and petrology of such systems. Ferric-ferrous iron equilibria (Fe^{3+}-Fe^{2+}) in magmatic rocks, for example, can be used to determine temperature and oxygen activity histories of magmatic rocks. Virgo and Mysen observed that the crystal-chemical behavior of iron in the important mineral clinopyroxene differs greatly from that previously suggested. They suggest that whereas in coexisting liquid essentially all iron occurs as Fe^{3+}, in the temperature and oxygen fugacity ranges of natural magmatic liquids the iron in clinopyroxene is Fe^{2+}. An understanding of this behavior could lead to revised models of the role of iron-bearing minerals in magmatic rocks.

That volatiles like water and fluorine are important components

of magmatic liquids is seen in the composition of igneous rocks and in commonly observed explosive volcanic activity. Various experiments have demonstrated that dissolved volatiles affect the composition of crystals and liquids in predictable ways, and that melts containing volatiles are altered structurally and in their properties.

Several research ventures at the Geophysical Laboratory seek a structural basis for predicting properties of volatile-bearing magmatic liquids. Mysen and Virgo find that H_2O interacts with oxygen in melts to form OH-bearing structural complexes with all major elements. Whereas earlier models commonly considered water solubility mechanisms in terms of random mixing of OH groups in the silicate melt structure, Mysen and Virgo observed that as many as two oxygens of the four in silicon-oxygen tetrahedra will be replaced by OH groups. In addition, aluminum, calcium, and sodium interact with H_2O to form additional hydroxyl complexes. From calculation of their free energies of formation, the relative stabilities of the associated hydroxyl complexes were found to be, in decreasing order, those of Si, Na, Ca, and Al.

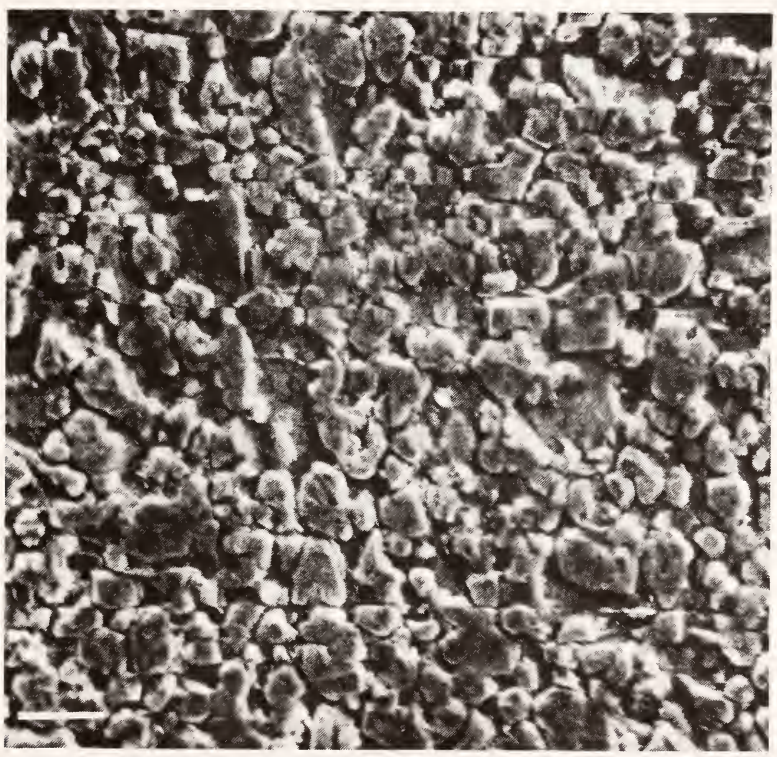
In an associated study, Mysen and Virgo found that fluorine dissolves similarly but that the relative stabilities of fluorine complexes differ in a conceptually similar manner (with F^- as OH^- groups forming analogous complexes) but that the relative stabilities of fluorine complexes differ systematically from those of hydroxyl. These studies led to a model predicting a melt structural basis for the flow properties of hydrous, fluorine-bearing liquids—behavior in accord with laboratory observations by Dingwell and Mysen. Dingwell and Mysen also examined relations between viscosity and water or fluorine contents of natural aluminosilicate liquids (granite, rhyolite, and associated rocks); they noted that the presence of a small percentage by weight of fluorine or water in granitic and rhyolitic magma is probably a requirement to reach values of viscosity and density necessary for such major rock-forming processes as magma aggregation, migration, and crystallization in the Earth and planets.

The Formation of Minerals and Rocks. Petrology was perhaps the first of the natural disciplines for which the need was recognized for experimentation. Early in the century, this circumstance led directly to the founding of the Geophysical Laboratory. Since then, the Laboratory has stressed the chemical and physical-chemical aspects of petrology, probably because variations in bulk composition are among the most conspicuous properties of rocks. Nearly all the work in experimental petrology at the Laboratory is concerned with processes generating marked changes in the bulk compositions of igneous and metamorphic rocks or differences in the minerals and mineral assemblages they contain.

Hatten Yoder has been tracing the nature and extent of depar-

tures from equilibrium cooling that might generate mutually incompatible phase assemblages in the potash-rich igneous rocks. Changes in temperature and water pressure, for example, may alter the previous compatibility of pairs of minerals, and new assemblages may become stable under the new conditions. From textural relations in actual rocks and experimental demonstration of the reaction, it is often possible to infer the direction of reaction and the sequence of changing conditions that have affected a rock.

Such departures from equilibrium may include reheating and attendant remelting or partial melting. In much of contemporary petrological speculation, the mechanism and consequences of partial melting are of central importance; yet this complex thermal process has never been examined mathematically or experimentally in proper detail. The experimental difficulties are formidable. To model the simplest forms of the process (the transfer of heat from an external plane source, for example), a rather large block of material must be brought to some initial temperature and then, while a controlled amount of heat is supplied to it at some fixed rate over a considerable period of time, the distribution of temperature within it must be monitored periodically at many sites.



In a demanding series of experiments, Hatten Yoder at the Geophysical Laboratory modeled mechanisms and consequences of partial melting under conditions representative of the inner Earth. Shown here is a photomicrograph of the composition nepheline 85.8–sodium disilicate 14.2, after heating for 24 hours at 1172°C and 1 atmosphere. The blocky crystals of nepheline, set in an etched groundmass of glass, illustrate the extent of crystal bridging. Thus, the material in the Earth would have behaved as a solid, though permeable and rather plastic. The bar is 15 μm.

Yoder has recently completed a successful investigation of this type. At the maximum temperature of 1170°C, the sample was 40% melted; yet "crystal bridging" was maintained. Thus, in the Earth's crust, material under these conditions would have continued to behave as a solid, though permeable and rather plastic. This work paves the way for extensive experimentation bearing on the heat-transfer aspects of petrological problems.

Yoder's research is concerned with developmental changes experienced by a single parent liquid, whereas staff member T. Neil Irvine is studying phenomena he thinks best explained by the mixing of two such liquids. Irvine is conducting a long-range investigation of layered intrusions—bodies of igneous rock formed by the slow crystallization of magma beneath the surface. As the molten material cools, minerals crystallize in ordered sequence to form layers, some of which may contain ores in useful concentrations. As part of this study, Irvine and Martin Sharpe of the University of Pretoria are examining the distribution of the spinellid minerals chromite and magnetite in the Bushveld complex in South Africa.

The Bushveld is the world's largest known layered intrusion, a body 450 × 350 km in plan and 9 km thick. At stratigraphically deep levels in the complex, it contains fifteen chromite layers, typically from 10 cm to 1 meter thick; at upper levels there are some 25 magnetite layers, usually from 10 cm to 2 meters thick. Layers of both types extend for many kilometers, and some of each type are interstratified with anorthosite and ultramafic or mafic rocks. From earlier work (*Year Book 81*, *82*), Irvine and Sharpe are persuaded that the intrusion as a whole has been formed by the injection and mixing of two magmatic fluids, one initially of ultramafic composition, the other anorthositic. Through laboratory work in which they melted naturally quenched samples of these magmas, they have found that in mixtures of the two, the first mineral to crystallize is chromite, even though the ultramafic liquid by itself first crystallizes olivine and the anorthositic liquid by itself first crystallizes plagioclase. This result is regarded as strong evidence that the chromite layers of the complex were produced by mixing of the two magma types.

The crystallization of magnetite cannot be studied in similar experimental fashion because naturally quenched samples of the appropriate parent magmas have not been found. Irvine points out, however, that the mixing effect discovered experimentally for chromite can be realistically modeled in a comparable synthetic system and that, in this system, the same effect is observed for magnetite when its components (FeO, Fe_2O_3) are substituted for those of chromite (MgO, Cr_2O_3). It appears, therefore, that under certain conditions associated with iron enrichment of the magma by fractional crystallization, the mixing effect might indeed also yield magnetite layers.

Gregory Muncill, the W. M. Keck Foundation Research Scholar in the Earth Sciences, is concerned primarily with the rate and manner of crystal growth. He has been directly determining the rates whereby plagioclase crystals grow in relatively simple melts of rocklike (haplogranodiorite) composition. Under immediately subliquidus conditions, early first-phase growth rate is linear, and the crystals are platelets of essentially equilibrium composition. Employing electron microprobe traverses across the crystal-liquid interfaces, Muncill observes that with increased undercooling, measurable compositional gradients develop in the liquid immediately adjacent to growing crystals. The gradients extend only tens of micrometers from the interfaces, however, and there is no indication of zoning in the crystals. (A zoned crystal has a different chemical composition in its inner and outer parts.) Muncill concludes that the complex and reverse zoning frequently observed in natural plagioclase must be a response to departures from steady-state conditions during crystallization. He is currently designing equipment whereby he can include changes in pressure and temperature as experimental variables; he is also making a detailed geochemical field study of a granodiorite pluton, the plagioclase of which is complexly zoned.

The gradients in composition noted by Muncill are obviously diffusion controlled. (Each gradient in the liquid characterizes the rate at which material transferred from liquid to growing crystal is resupplied from parts of the charge remote from the crystal.) Such diffusion-controlled composition gradients may prove to be important in connection with local phenomena like the development of zoning in phenocrysts or the growth of reaction rims about them. On the whole, however, the amount of material transported and the distance are thought to be rather small.

Material transport of much greater magnitude, possibly in part dependent on diffusion of a rather different type, is involved in the work of staff member John Frantz. Frantz studies the large-scale metasomatic, or chemical, processes accompanying the development of metamorphic rocks within the Earth. Transport through the bulk Earth of the amounts of material required in metamorphic processes seems quite beyond the capacity of the diffusion of the intragranular sort involved in Muncill's experiments. There is general agreement, however, that in most metasomatism diffusion occurs in a thin grain-boundary film of fluid, which receives matter being dissolved from a mineral and is itself subjected to convectively or tectonically driven transport. The dissolved matter contained in this intergranular fluid ultimately reprecipitates or reacts with a host rock when, at some later time and possibly quite distant site, it encounters appropriate pressure, temperature, and other conditions.

Frantz addresses various aspects of the composition of the intergranular supercritical fluids—the solubilities of rock-forming

minerals, the ionic behavior of dissolved components, and the identities of transition-element complexes in them. During the past year, he has studied the Raman spectra of high-temperature, high-pressure aqueous fluids, using a specially designed optical cell having either sapphire or diamond windows. Working with pure water, Frantz has demonstrated the disappearance of tetrahedral bonding with increasing temperature and decreasing density. He notes that the envelope containing the O-H stretch frequencies narrows under these conditions, indicating a possible decrease in the number of other coordinations of water. In dilute aqueous solutions of zinc chloride, he finds that with increase in temperature and decrease in density the dominant species changes from $ZnCl_4^{2-}$ to $ZnCl_2$, in accord with decrease in the dielectric constant of water. He is now attempting to compute association constants for these complexes.

Frantz and others attempting to devise experimental or numerical models of metasomatic replacement are acutely aware that although the observed scale of this phenomenon in nature often implies solution and transport of enormous amounts of dissolved matter by infiltrating fluids, there is little direct evidence for, and much skepticism about, such large-scale infiltration. Persuasive evidence that fluid circulation is indeed a phenomenon of major importance has recently been obtained, however, by close examination of a very small part of an exceedingly rare but ubiquitous mineral.

This evidence comes from graphite found by staff member Douglas Rumble in many post-orogenic quartz veins cutting intrusive and metamorphic rocks throughout central New Hampshire. Rumble and Thomas Hoering have shown that the ratio of stable carbon isotopes in this graphite varies widely between limiting values characteristic of the two great crustal reservoirs of carbon—biogenic carbonate and biologically reduced carbon. Rumble and Hoering propose that (1) metamorphism of shales containing reduced organic matter generates aqueous fluids in which $CH_4 > CO_2$, (2) metamorphism of argillaceous limestones yields aqueous fluids where $CH_4 < CO_2$, and (3) precipitation of graphite occurs when aqueous fluids with different CH_4/CO_2 are mixed. This theory is consistent with their carbon isotope data, for carbonaceous matter in fluids derived from organic shales is relatively poor in ^{13}C and that from carbonate-rich rocks is relatively rich in that isotope. One would expect then that the ^{13}C content of graphite precipitated by fortuitous mixing of such fluids would be intermediate, as indeed they find to be the case in much of the New Hampshire granite examined to date.

Mineral Physics and Its Application to the Inner Earth

For many decades, the principal task of the mineralogist was

simply to describe and classify physical, chemical, and structural properties of natural inorganic crystals. As these data gradually accumulated for most species, however, mineralogists increasingly sought to identify physical and chemical principles that underlie mineral formation and behavior, as well as procedures that might lead to predictions of mineral stability conditions and properties deep within the Earth. Mineral physics, which has evolved from traditional mineralogy during the past two decades, is the study of mineralogical problems through the application of principles of condensed-matter physics and chemistry.

Mineral physics bridges gaps among a number of disciplines. It is inevitably linked with traditional fields in earth science, including solid-earth geophysics, geochemistry, crystallography, petrology, and geodynamics. Close ties also exist with aspects of ceramics research, materials science, physical chemistry, high-temperature and high-pressure studies, and solid-state physics. The range of materials studied parallels the diversity of the mineral kingdom itself, including elements, metal alloys, sulfides, halides, layer compounds, and zeolites, in addition to rock-forming oxides and silicates. Experimental work has intensified with the finding of new industrial applications—in the manufacture of lasers, high-performance ceramics, molecular sieves, catalysts, and a variety of electronic components.

The technology of mineral physics, too, is highly modern. Spectroscopic techniques that probe atomic vibrations and elasticity of minerals are now coupled with procedures to deduce atomic chemistry and structure with ever-increasing precision and spatial resolution. Concurrently has come the remarkable development of high-pressure and high-temperature apparatus for measuring mineral structures and properties under geologically relevant conditions.

Scientists at the Geophysical Laboratory have been pacesetters in mineralogical research since the pioneering studies by Day, Allen, and others in the first decades of this century. Carnegie researchers achieved many firsts—the first high-temperature crystallographic studies by Wyckoff in the 1920s, the first geological applications of Raman spectroscopy by Hibben in the 1930s, determinations of element partitioning from the Mössbauer effect by Virgo in the 1960s, and the attainment of record high static pressures by Mao and Bell in the past decade. The Laboratory's tradition of leadership continues in today's mineral physics.

A Polyhedral Approach to Mineral Compression. Of particular interest in studying the Earth's interior is the compressibility of materials—how a mineral's volume changes with pressure and temperature, or its "P-T-V equation of state." X-ray diffraction experiments on crystals at high pressure reveal the subtle shifts in atomic positions that accompany crystal compression, and

provide a quantitative measure of the compressibility. Staff members Robert Hazen and Larry Finger have observed that mineral compression can be explained by means of the regular arrangements of cation-anion clusters, or polyhedra, which recur repeatedly in often-complex crystal structures. Most mineral compression can be described as some combination of (1) compression of polyhedra, (2) bending of angles between polyhedra, and (3) intermolecular compression.

The beryllium aluminosilicates are ideally suited for a combined experimental and theoretical study of mineral behavior, thereby exploring the polyhedral approach. These minerals are available in large, perfect crystals well suited to many different experimental procedures; furthermore, all the component atoms are electronically simple, thus facilitating computational quantum techniques. As part of a continuing study of beryllium minerals, Hazen, Finger, and research associate Andrew Au recently determined high-pressure crystal structures for a suite of beryllium aluminosilicates. They found that beryllium tetrahedra act the same as silicon tetrahedra in these structures. Physical properties of several beryllium minerals may thus be understood in terms of a framework of beryllium and silicon tetrahedra.

Andrew Au extended the polyhedral approach to model the elastic properties of the beryllium minerals. He has demonstrated that elasticity of the minerals bromellite, corundum, and chrysoberyl can be modeled by assigning fictive polyhedral elastic constants to beryllium tetrahedra and aluminum octahedra.

Vibrational Spectra and the Properties of Materials. Underlying mineral physics research at the Geophysical Laboratory is a growing awareness of the dependence of macroscopic properties—particularly those that govern geophysical processes—on atomic-level interactions. Efforts are under way, therefore, to document relationships among mineral structure, bonding, physical properties, and stability. Postdoctoral fellow Anne Hofmeister and staff member Thomas Hoering have investigated the dependence of heat capacity—a fundamental macroscopic property of minerals—to atomic vibrations by measuring the infrared spectra of a series of beryllium minerals and applying the Kieffer lattice dynamic model to the data. For beryllium silicates with known band assignments, heat capacities calculated from the observed vibrational frequencies matched values determined by calorimetry within a few percent.

Staff associate Martha Schaefer and Hofmeister used the same approach to study vibrational spectra of iron oxides and sulfides. Preliminary data on the iron silicate fayalite indicate that magnetic contributions to heat capacity may be very important in modeling iron-bearing materials. Further investigating the magnetic behavior of iron in minerals, Schaefer and David Virgo conducted Mössbauer spectroscopic studies of the iron oxide wüstite at high

pressure. They observed a gradual phase transition from the paramagnetic to the antiferromagnetic state between 100 and 200 kbar. This magnetic alteration in a major component of the Earth's mantle may be critical for understanding the role of iron in the Earth.

Heat capacities of minerals at high pressure are at present impossible to measure directly. Hofmeister, visiting investigator Ji-an Xu, and colleagues at the Laboratory have successfully obtained far-infrared spectra of olivine, silicate spinel, and alkali halides held at pressures up to 300 kbar. From the observed shifts in vibrational frequencies, they have deduced that heat capacity decreases linearly with pressure in the magnesium-iron silicate, olivine. Values for the Earth's adiabatic temperature gradient calculated from these olivine data agree with values obtained from seismological data, and thus lend credence to the spectroscopic approach.

Laboratory Explorations of the Mantle. The several experimental studies of the Earth's transition zone (lying between 400-km and 670-km depth) and lower mantle can be viewed as a comprehensive investigation at high pressure of the broad system FeO-Fe_2O_3-MgO-CaO-Al_2O_3-SiO_2. The experiments are leading to determinations of cation coordination, phase transitions, density as a function of pressure, and the Gruneisen parameter, and are complemented by theoretical studies of molecular bonding and lattice dynamics of mantle minerals.

Of fundamental importance in mantle geochemistry is the question of the bulk composition of the transition zone. Seismic studies provide observational data on various properties of the region and how they change with depth. Attempts to satisfy the seismic data in mineralogical models have shown extreme sensitivity to variations in composition. Thus, laboratory determinations of the pressure-volume relations of candidate materials promise to set valuable constraints on the possible composition of the region.

In three separate studies, Ji-an Xu, Ho-kwang Mao, and Peter Bell have determined pressure-volume relations in the garnet phases grossularite ($Ca_3Al_2Si_3O_{12}$), almandite ($Fe_3Al_2Si_3O_{12}$), and andradite ($Ca_3Fe_2Si_3O_{12}$) at pressures to 400 kbar. The experiments were performed with the diamond-anvil, high-pressure cell developed at the Laboratory (*Year Book 83*, pp. 74–77). Pressure was transmitted to the samples through a quasihydrostatic solid argon medium, through which x-ray diffraction measurements of unusually high resolution and precision were possible. The new data—the first obtained on mantle minerals at the higher pressures—are being analyzed to determine the roles of calcium, aluminum, and ferric iron in garnet and thus to set constraints for possible transition-zone composition. Meanwhile, the same investigators also examined phase transitions in the scheelite structure at

high pressure. Results of these studies, along with infrared and Raman spectra in olivine measured by Hofmeister, Xu, and colleagues and postdoctoral fellow Russell Hemley, are being used in developing models of the mantle.

Experimental data on the deep-mantle oxide minerals CaO, (Mg, Fe)O, and Al_2O_3 were obtained in a study by postdoctoral fellow Pascal Richet with Mao and Bell, also at quasihydrostatic pressures (to 1 Mbar). An expected transition in CaO was observed at 650 kbar, reversed equilibrium was demonstrated, and the equation of state in the higher pressure phase determined; results compared well with the theoretical calculations of Hemley. Compressibility data for the other two minerals were obtained to 500 kbar. The work extends the laboratory data forming an essential base for models of the deep mantle.

Computational Quantum Chemistry. Experimental studies are complemented by computational quantum chemistry, which has led to predictions from first principles of mineral structure, stability, and physical properties. Larry Finger, collaborating with Gerald V. Gibbs of Virginia Tech, has calculated optimum interatomic distances for a variety of ions and coordinations. Their theoretical results matched the experimental data obtained by many researchers from x-ray crystallographic analysis of mineral structures. Finger and Gibbs then calculated bonded radii from the theoretical charge distributions and found that radii of anions were much smaller than most workers had previously estimated. Further, these radii were affected by the cation, as well as the anion, coordination—an unexpected result. Extension of these results could provide additional information needed to predict mineral properties under conditions of the inner Earth.

Minerals between the transition zone and the core-mantle boundary (in a range of pressures from 225 kbar to 1.5 Mbar) are believed to be confined in major components to the FeO-MgO-SiO_2 portion of the system. In an important complement to the previous experimental data of Mao and Bell, Russell Hemley and colleagues at Harvard have employed another computational quantum technique—the electron gas method—to model equations of state, lattice dynamics, and elastic properties of such materials. Their results predicted the predominance of a silicate perovskite structure ($MgSiO_3$) in the lower mantle. The calculations employed a first-principles, parameter-free model including lattice dynamics; results were extended beyond 1 Mbar at temperatures of 298, 1000, and 2500K including the volume equation of state for silicate perovskite. Similar calculations were performed for the component oxides MgO and SiO_2. The pressure dependence of thermal expansion of MgO, an essential quantity for geophysical models of the deep Earth, was also calculated. Director Yoder writes, "these studies represent a pioneering application of first-

principles theory for understanding fundamental properties of high-pressure mineral phases." Hemley's work complements the Laboratory's experimental studies of the same systems at high pressure in late years, as well as Richet's recent study of compression in calcium oxide.

The Approach to the Earth's Core. Experiments at still higher pressures require the most advanced state-of-the-art technology, much of it developed at the Geophysical Laboratory. During the past year, investigators Ho-kwang Mao, Peter Bell, and Kenneth Goettel extended the maximum achievable static pressures for routine experimentation to the range of 2–3 Mbar. Although pressures beyond 1.8 Mbar had previously been sustained, calibration techniques for the higher pressures depended on calculation of the stress field. Mao *et al.* employed new spectroscopy techniques involving diode-array imaging detectors to make calibrated pressure measurements to 2.5 Mbar using the familiar ruby-fluorescence scale.

The ruby scale was itself calibrated to above 2 Mbar by Xu, Mao, and Bell by measuring the volume equations of state of gold, copper, silver, and tantalum in the diamond-anvil apparatus and by cross-referencing data for these metals known from shock-wave experiments.

In further work toward experimentation at core pressures, the Geophysical Laboratory workers developed a micro-focus Raman spectroscopy system to explore the Raman shift behavior of diamond itself. (In the high-pressure apparatus, diamonds serve as windows and as anvils for squeezing the sample.) By calibrating the Raman shift with pressure, the investigators obtained a basis for mapping out the stress field within the diamonds under high pressure. The resulting three-dimensional stress distributions will be used in conjunction with finite-element design analysis to attain design improvements for generating still higher pressures.

Andrew Jephcoat, with Mao and Bell, has conducted experiments studying the equations of state of metallic Fe, Si, and FeS_2 to pressures of roughly 1 Mbar. The object was to obtain pressure-density relations for comparison with seismic observations. The effort is part of an extended program to determine which iron-rich compositions are compatible with seismic data from the core. Results of the new experiments, done under quasihydrostatic conditions, compare well with earlier shock-wave data.

Toward Understanding Earthquakes

The members of the seismology group at DTM have for some years led in developing borehole strainmeters—instruments which, when emplaced in subsurface rock, are capable of detecting and recording minute changes in earth deformation over extended

time. Today, strainmeter data are proving of extreme interest in helping increase understanding of earthquakes.

The first borehole strainmeters were developed in the 1960s by Selwyn Sacks of DTM and Dale Evertson of the University of Texas at Austin. DTM engineers and technicians—Michael Seemann, Glenn Poe, and John Doak—have made critical contributions over the years to the design of the instrument and its associated electronics. The strainmeter is essentially a resiliant, liquid-filled tube, which is cemented to rock at the foot of a borehole reaching 200–400 meters beneath the surface. Changes in rock deformation as small as one part in 10^{11} can be detected. The instrument has uniform sensitivity to strain over a wide range (from zero frequency to several hertz). Prototype versions were tested on the DTM campus, and the first deployment in an active seismic area (Matsushiro, Japan) proved successful.

Since then, nets of DTM-built strainmeters have been emplaced in several areas of major earthquake activity around the world. Staff members Selwyn Sacks and Alan Linde have worked closely with scientists abroad interested in the strainmeter as a possible aid to earthquake prediction. In each of the several installations to date, scientifically useful data has already been used to study earthquakes and the Earth's crust, and to identify processes where stress is redistributed in active tectonic regions.

The initial Matsushiro installation, for example, led to information on seismic waves and permanent deformation caused by small, local earthquakes. Use of the strainmeter data together with data from a DTM broadband seismograph at the same site, enabled investigators to improve knowledge of the exact location and physical properties of nearby earthquakes. Meanwhile, several instruments were installed in a South African gold mine, more than 3 kilometers below the surface. Many strain steps were recorded, which were shown to be related by simple elasticity to the sizes of the corresponding earthquakes.

In 1980, not long after the installation of instruments at seven sites in the region, an eruption occurred of the volcano Hekla in southern Iceland. All instruments recorded strain changes. These were used to provide a model of the mechanism for the eruption and recharge of the magma chamber beneath the volcano. Subsequently, a series of unusual strain signals have been observed at the site in Iceland closest to the transform fault linking segments of the great mid-Atlantic ocean ridge. Further strain data, and perhaps subsequent seismic events in the region, may unlock understanding of these signals. The instruments continue to record data continuously.

A similar series of unusual strain signals was later observed at a site in the western part of Tohoku in northern Honshu. The signals appeared to be related to a large earthquake occurring in the Japan Sea, though evaluation of the signals as possible

precursors of the earthquake awaits more data. The station was one of three installed in cooperation with Tohoku University, whose personnel also obtain regular measurements of seismograph, extensometer, and tilt data.

Data from the southern Honshu net (installed and operated by the Japanese Meteorological Agency) have allowed the identification of slow earthquakes, or "slowquakes"—events resembling earthquakes except over much longer time periods. A major slowquake took place immediately after the Izu-Oshima earthquake of 1978, south of Tokyo. Strain data from three nearby strainmeters allowed DTM scientists and their Japanese colleagues to determine the character of the slowquake. Knowledge of that additional fault movement made it possible to explain the observed vertical motions in the Izu peninsula. Later, over a 30-month interval in 1978–1980, a significant tectonic event occurred nearby. Slow strain changes were detected at many stations, and calculations showed that this very-slow event had a cumulative size equivalent to a massive (magnitude 8) earthquake.

A number of strainmeters have been installed in California, mainly in areas of high earthquake probability along the San Andreas Fault. (Collaborating with the DTM group are workers from the U.S. Geological Survey and the University of California, San

Recent borehole strainmeter installation in California. The sensing apparatus, connected by wire to recording instruments on the surface, will be lowered and cemented into subsurface rock. Volume deformations of the instrument will provide data on subsurface strain over extended periods. Seismologists at the Department of Terrestrial Magnetism have developed these instruments and are using them to study characteristics and possible precursors of earthquakes.

Diego.) Instruments in the Parkfield area have recently shown a number of strain changes, days in length. These seem to be evidence of slow events on the fault, and have been followed by small nearby earthquakes.

A valuable innovation at some of the California sites is the use of recorders capable of recording high-frequency signals. Although the strainmeter devices were previously capable of sensing such signals, their recording would have required massive amounts of magnetic tape. The new devices are triggered so that they record only when a disturbance is present; at other times, the data telemetry system provides a low sampling rate. The recorded data, at frequencies as high as 100 hertz over long periods, will improve the present ability using the local seismograph net to determine seismic moment and other properties. Small strain steps will also be detectable, thus supplying a further measurement for determining source properties. Comparable improvements are being introduced in Iceland, where data has been recorded only at the local sites, on chart paper.

The DTM programs in Japan, Iceland, and California are continuing, owing in large part to the active collaboration of investigators in these countries. Meanwhile, a net of seven instruments is being installed in the central region of Peru, in cooperation with the Instituto Geofísico del Peru (IGP). The area being monitored has a history of large and damaging earthquakes, along with generally high seismicity. The strain data will complement data from a new seismograph net, also established as a result of collaboration between DTM and IGP. Data are telemetered to a computer in Lima, so that seismic activity can be monitored instantaneously. Data from the two systems—the strainmeter and seismograph—should contribute to understanding of the oceanic Nazca plate subduction beneath the South American continent. (See page 86.)

Another strainmeter net is being installed in mainland China, where interest in earthquake prediction is strong. The effort is in collaboration with the State Seismological Bureau of the People's Republic of China. Data should provide an opportunity to study large intraplate earthquakes—phenomena that occur only rarely in the United States.

The strainmeter program has added to our understanding of earthquakes and has enabled scientists to identify previously unrecognized processes leading to stress redistribution in the Earth. Strainmeter measurements taken at depths of hundreds of meters are far more reliable than earlier deformation measurements by short-baseline techniques at the surface. The new projects in Peru and China, along with the improvements in data acquisition, should add significantly to the growing bank of high-quality data needed for frontier investigations of earthquakes and stress redistribution.

An On-Land Spreading Event? Last year, staff member Paul Silver and postdoctoral fellow Tetsu Masuda of DTM proposed that two earthquakes in California and Baja California were manifestations of episodic on-land spreading (*Year Book 83*, pp. 90–92). In spreading, material at the surface slowly moves in opposite directions away from a center of spreading, probably as a result of material upwelling from below. Spreading is a common phenomenon along the midocean ridges, but only two on-land centers of active spreading are generally acknowledged—in Iceland, and in the Afar (eastern Africa); these represent rare opportunities to observe the spreading process in detail.

Now, Silver and research associate Nathalie Valette-Silver have collected data from various sources, investigating whether certain characteristics were present in the Cerro Prieto region near the U.S.-Mexico border, between the centers of the two earlier earthquakes. They examined evidence of four conditions, each of which should have been present if indeed on-land spreading was taking place: (1) increased seismic activity, (2) crustal extension in the assumed spreading direction, (3) terrain subsidence, and (4) a thermal event presumably reflecting the movement of magma. A large quantity of past observational data are available, primarily because of the presence at Cerro Prieto of a geothermal field, which has been closely monitored since 1970.

Silver and Valette-Silver's study indicated that all four characteristics were present. (1) Transform faults just to the north and south of Cerro Prieto failed within eight months of each other, (2) geodetic measurements confirm that the land extended in the assumed spreading direction, (3) leveling data and measurements of changes in the gravity field are consistent with tectonically induced subsidence, and (4) the temperatures of nearly all the 27 wells in the geothermal field registered a rise of about 3°C between the times of the two earthquakes—the kind of signature that would be expected from the movement of magma.

The results also suggest applications in understanding the earthquake process. For example, it is not known whether the movement of magma causes transform fault events or vice versa. The fact that this thermal event preceded at least one of the earthquakes studied, suggests that the movement of magma may come first. If so, then the seismic activity in such regions may be predictable from thermal evidence.

Biogeochemistry

The program in biogeochemistry at the Geophysical Laboratory dates back to 1953, when Philip Abelson discovered that many fossils contain amino acids, which survived for millions of years apparently protected, for example, by the dense structure of an

Andrew Giże at the Geophysical Laboratory studies organic material associated with ore deposits. Shown here is a droplet of bitumen, now thermally altered to a fine mosaic texture, in a vein from the Carlin gold deposit, Nevada. The outer rim is interpreted as an oxidation reaction, indicative of the oxidation state of surrounding fluids during thermal alteration. Such insights into ore solutions can be valuable for understanding the process of ore formation.

organism's shell. More recent research in biogeochemistry has investigated the chemistry of these amino acids, determining their stability and obtaining correlations between laboratory tests and fossil data. A related line of study has emphasized the mineralization of organic materials—the growth of crystals of carbonate, phosphate, sulfate, iron oxide, and other products, to attain the fossil forms now seen. In April 1985 the Geophysical Laboratory hosted an international conference, *Biomineralization Processes and the Fossil Record,* which focused on both modern and fossil organisms. Participants explored the role of the organic matrix both as a template for mineralization and as a preservative of fossil biominerals.

The same topics are seen in much of the current research of the biogeochemistry group at the Laboratory. Staff member P. Edgar Hare and Heinz Lowenstam, visiting scholar from Caltech and once Hare's mentor there, are studying shell of the brachiopod *Lingula,* which is hardened by the presence of carbonate apatite, a mineral found also in vertebrate bones and teeth. *Lingula,* a still-extant organism whose ancestors are found throughout 600 million years of the fossil record, is of particular interest because its biochemistry is a mixture of invertebrate and vertebrate processes.

Meanwhile, Michael Alcorn of Harvard and Hare have been studying the preservation of collagen and other proteins in an extraordinary collection of 2000-year-old human bones from the Middle East. The specimens have been exceptionally well preserved during long burial in the dry desert. Levels of nitrogen and amino acid concentrations approach those in modern material, and although the bone proteins show some breakdown, some of the

original organic matrix is preserved and may prove comparable to modern bone. An exciting aspect is the application of immunological techniques in studying individual proteins; in preliminary results, Alcorn and Hare have identified the presence of proteins in the fossil specimens that react to the same antibodies as the analogous proteins in modern bone. Study of the detailed protein chemistry of ancient materials thus may be possible.

In his continuing study of the chemistry of fossil bones, postdoctoral fellow Thomas Stafford is developing new techniques for isolating peptides from proteins that have been altered by diagenetic processes. He is also addressing the carbon and nitrogen isotopic compositions of fossil proteins, which can be related to an ancient animal's diet and environment. In fossil *Bison* bones from sediments 500–13,000 years old in the Texas panhandle, he finds that the relative carbon isotope ratio $\delta^{13}C$ decreases with increasing geologic age. Stafford believes that this is evidence of a change in diet, from grasses having one kind of photosynthetic pathway (the C_3 type) to another (the C_4 type). The implied change from a cooler, wetter climate to a hotter, drier one is compatible with sedimentary evidence representing the last 13,000 years.

Geophysical Laboratory staff members Marilyn Estep and Thomas Hoering are lending their experience in stable isotope work in collaborative work with investigators at the Department of Plant Biology (see pp. 47–48). Isotopic measurements are also proving useful for identifying sources of organic matter in estuaries. Predoctoral fellow L. A. Cifuentes (University of Delaware) and staff member Marilyn Estep are studying organic material suspended in the Delaware Bay, investigating the roles of the various riverine, sewage, marsh, and marine sources. Cifuentes and Estep observed seasonal variations in isotope ratios, which reflected seasonal patterns of river run-off, primary productivity, and remineralization. Fluctuations in $\delta^{13}C$ occurred independently of those in $\delta^{15}N$. Nitrogen ratios were strongly influenced by springtime nitrification upriver; the phytoplankton bloom in spring of 1984 and 1985 had a high $\delta^{15}N$, as a result of phytoplankton uptake of isotopically heavy nitrogen in the ammonia pool remaining after nitrification. This research is important in its coupling of biological and environmental factors with isotopic measurements.

A Quest for the Molecules of Ancient Life. A major objective in studying the nature of early life is to isolate a molecular fossil—a molecule from a fossil or sediment whose structure can be traced backwards over time (applying known processes) to determine the exact nature of ancient cell material. The only likely molecular fossils that persist for great lengths of time are hydrocarbons.

For over two decades, staff member Thomas Hoering has sought to isolate molecular fossils in rocks of widely varying age. A promising raw material is kerogen, a high-molecular-weight, insolu-

The biogeochemistry group at the Geophysical Laboratory. From left to right: P. E. Hare, H. Lowenstam, Marilyn L. Estep, T. W. Stafford, Jr., Thomas C. Hoering, Andrew Giże.

ble material that is the primary form of organic matter buried in sediments. Kerogen contains molecular fossils that are bonded tightly into its structure and are relatively free of contamination.

Hydrous pyrolysis is a simple method for mildly breaking down kerogen. First, kerogen is isolated from rocks and carefully extracted with solvents to remove potential contaminants. The kerogen is then heated in a pressure vessel in the presence of excess liquid water for several days at 330°C. During the past year, Thomas Hoering and Vivek Navale, visiting investigator from the University of Maryland, carried out hydrous pyrolysis of rocks 500–3300 million years in age; the investigators analyzed the hydrocarbon products for five classes of molecular fossils.

Small amounts of such compounds could be obtained in the younger samples, but the amounts obtainable decreased steadily with age in older rocks, even in sediments having well-preserved minerals. Thus the amounts and kinds of hydrocarbons that could be isolated from kerogens older than 1600 million years approached those found in blank and control runs. The most common molecular fossils observed were normal hydrocarbons; isoprenoid and triterpane hydrocarbons were found in only a few cases. The search for sterane hydrocarbons gave at best ambiguous results. Organic molecules appear to be too labile and reactive to persist for longer times, even under the best of circumstances.

Professional Activities

The Educational Role. In *Year Book 49*, Vannevar Bush, then president, made a careful assessment of the Institution's post–World War II role. He noted that Carnegie staff members were fortunate in not being distracted by the many duties that are inevitably a part of the operation of a great university. But he also noted a key distinction that was not so favorable. While university professors necessarily came into daily contact with young minds, he wrote, Carnegie scientists, if they so desired, could avoid all such contact.

The fellowship program that Bush initiated in the late 1940s was partly designed to correct this potential isolation. But it was also designed to provide advanced training for young scientists. Today, augmented by grants from the Carnegie Corporation (a program begun during Caryl Haskins's presidency) and other sources, the Institution's educational role is one of its most important and satisfying efforts. About 130 individuals served in the Institution's departments as postdoctoral fellows, research associates, predoctoral fellows, and students during the report year.

Individuals are chosen with care, with an eye to their independence and self-motivation. They are often selected because of the significance of their research interests and how these interests complement those of the staff members. In astronomy alone, as we have seen, contributions by fellows this year ranged over all areas of the Institution's leading work; already recognized throughout the profession are the results of Kirk Borne's numerical simulations of interacting galaxies, Rogier Windhorst's ultradeep radio observations of extremely distant galaxies, Wendy Freedman's photometry of stars in nearby galaxies, Deidre Hunter's work on star formation in irregular galaxies, Belva Campbell's on young stellar objects, and Nicholas Suntzeff's on the chemical compositions of old, evolved stars. Postdoctoral fellows and grant-supported associates in the earth sciences and at the Departments of Embryology and Plant Biology are making comparable contributions.

In the departments, all scholars are treated as peers; fellows and research associates are encouraged to participate fully in seminars and symposia. As a result, they gain not only scientific knowledge and experience, but self-confidence. When they have finished their tours at Carnegie (which last generally from one to three years), many emerge as leaders in their respective fields. Often, they become serious candidates for permanent staff appointments at the Institution. During the report year, for example, three of four vacant staff positions were filled, after exhaustive searches, by current or former postdoctoral fellows and research associates.

Postdoctoral fellows Nick Suntzeff, Wendy Freedman, Belva Campbell, Rogier Windhorst, and Edmond Giraud at the Observatories.

Seminars and Symposia. Attendance at scientific meetings is a requisite for anyone seriously pursuing a scientific career. Staff members and fellows attend and give papers at many conferences each year. They also deliver invited lectures at select gatherings. During the report year, these activities took Carnegie scientists to New Zealand, the People's Republic of China, Israel, Costa Rica, Italy, Japan, Canada, Switzerland, the U.S.S.R., The Netherlands, Greece, West Germany, Sweden, Spain, and Bolivia.

In addition to attending conferences and giving papers, Carnegie scientists often serve as conference organizers. This year, for example, Richard Pagano of Embryology was the chairman of the 1985 Gordon Conference on Lipid Metabolism. Joseph Gall, also of Embryology, organized the 44th Annual Symposium of the Society of Developmental Biology. Vera Rubin of DTM chaired a Space Telescope Working Group on Galaxies and Clusters. Arthur Grossman of Plant Biology was co-organizer of an international conference on *Chlamydomonas*, and P. Edgar Hare and Thomas Hoering of the Geophysical Laboratory organized a Carnegie-NSF conference on biomineralization.

Local Seminars. Each department holds seminars, usually once a week, where staff members, fellows, and invited guests discuss work in progress. These seminars, while presented at an advanced level, are generally attended by all staff, and so provide forums for the interdisciplinary exchange of information. At DTM seminars, for example, astronomers, geochemists, and seismologists join in discussions.

Occasionally, a department will sponsor a day-long or week-long workshop or symposium devoted to a particular topic of research. The Department of Embryology hosts an all-day seminar annually. This year, its eighth annual minisymposium, "Plants, Genes, Devel-

opment," was organized by staff associate Sondra Lazarowitz and graduate student Barbara Kirschner. It was held in November.

The Department of Terrestrial Magnetism and the Geophysical Laboratory jointly hosted a two-day workshop on the Earth's mantle on November 20–21. Organized by Paul Silver and Richard Carlson of DTM and Peter Bell of the Geophysical Lab, the workshop was attended by leading investigators from several universities.

The Geophysical Laboratory continued its tradition of hosting meetings of the Washington Organic Geochemistry Colloquium, the Washington Crystal Colloquium, and the Petrologists' Club. The Department of Embryology again hosted the evening Disease of the Month Club. The Department of Plant Biology continues its vigorous joint seminar program with plant biologists at Stanford University.

Leadership Roles. Carnegie staff were active this year in a variety of professional societies. They served on NSF, NIH, NAS, USDA, and Space Telescope committees and panels, sat on review boards, and were members of various editorial boards. They served in advisory positions to universities and other research organizations, and they were members of Ph.D. thesis committees. Thomas Hoering of the Geophysical Laboratory, for example, served on the thesis committees for four advanced degree candidates. Robert Hazen, also of Geophysical, is on the editorial board of four journals.

Occasionally a scientist devotes more time than he or she ordinarily would to outside activities, as when an important new program is being initiated. DTM's David James and Selwyn Sacks, for example, are heavily involved in the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) (see pp. 97–99). Felix Chayes of the Geophysical Laboratory has devoted a great deal of time to the International Geological Correlation Project (IGCP), which is designed to systematize the electronic storage, use, and retrieval of petrological data. He served this year as chairman of the new Subcommission on Data Bases for Petrology of the International Union of Geological Sciences. He was organizer of new IGCP Project 239, which conducts pilot studies, and he organized and ran a meeting of IGCP Project 163—IGBA, held in Lisbon, Portugal, in September.

Often, as a scientist's status increases, so too do his or her outside professional activities. This is reflected in the myriad activities of the Institution's directors. Donald Brown, director of the Department of Embryology, for example, served this year on visiting committees and advisory boards to the Whitehead Institute, the Scientific Review Board of the Howard Hughes Medical Institute, and Princeton University's Department of Molecular Biology, among others. He is also a member of the jury for the Passano and Lasker awards. George Wetherill, director of DTM, also served this year on two award committees—for the G. P. Merrill and J. L.

Smith awards. In addition, he is president of the Meteoritical Society and a member of the NAS Space Science Board and the NASA–IAU International Halley Watch Steering Committee.

At the Observatories, director George Preston serves on the Space Telescope Advisory Committee of the Space Telescope Science Institute. New activities of Hatten Yoder, director of the Geophysical Laboratory, include membership on Harvard's Ad Hoc Committee on Geological Science, membership on the Tellers Committee of the National Academy of Sciences, and service on the American Philosophical Society's Membership Committee. Plant Biology director Winslow Briggs, who last year was designated a Senior United States Scientist by the Alexander von Humboldt Foundation, spent the year in Freiburg, West Germany.

Margaret L. A. MacVicar, vice president of the Institution, is co-chair of the AAAS National Council for Science and Technology Education. She was also this year appointed a member of the Advisory Council, Carnegie Corporation Forum on Education and the Economy, and she was elected a trustee of the Research Corporation of America and a member of the Board of Directors, the Exxon Corporation.

Losses, Gains, Honors . . . .

The death this year of Aaron David Singer, executive officer of the Geophysical Laboratory, was a severe blow to his many friends and colleagues. Singer began his career with Carnegie in 1935, when, at the age of 16, he became clerk and assistant computer at DTM. In the evenings, he took accounting classes at nearby Columbus University, eventually earning his bachelor's and master's degrees. In 1953, Philip Abelson convinced Singer—then in private industry—to join the Geophysical Lab as office manager. For the next 32 years, until he died of cancer on March 13, 1985, Dave kept things running at the Laboratory.

John Rock, a former research associate at the Department of Embryology (from the mid-1930s until 1945), died on December 5, 1984, at the age of 94. Rock was a noted gynecologist and obstetrician who played a key role in the development of the birth control pill. He was, in 1944, the first scientist to fertilize a human egg in a test tube.

Resigning from the Board of Trustees this year were Franklin D. Murphy and Frank Stanton. Stanton was a trustee since 1963 and chairman from 1977 until 1979. Best known for his leading role in the professional broadcast field, he was for 25 years (1945–1971) president of CBS, Inc. At the meeting of the Carnegie Board in May, Dr. Stanton was designated trustee emeritus.

Two staff members—Douglas Fambrough and Typhoon Lee—re-

signed during the report year. Fambrough came to the Department of Embryology in 1969, shortly after receiving his Ph.D. at the California Institute of Technology. At Carnegie, he and his colleagues carried out the first critical biochemical analysis of the acetylcholine receptors on cell surfaces that mediate nerve-muscle interactions. He also explored the metabolism of other cell suface proteins, most recently the sodium pump. On July 1, 1985, Fambrough joined the biology department of Johns Hopkins University, where a neurobiology institute is in the planning stage. The Department's consolation in losing him, writes Donald Brown, is that he will be only ten minutes away.

The Department of Terrestrial Magnetism is not so fortunate. Typhoon Lee took a temporary leave of absence from DTM last year to establish an isotope geochemistry laboratory at the Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan. This year, Lee decided to remain in Taiwan, his native country, as an Academia staff member.

Several members of Carnegie's support staff retired at the end of the report year. John Doak, electronics research specialist, worked at DTM for 38 years before retiring in June. His skills proved invaluable in the development of mass spectrometric and seismology instrumentation. Harvey Moore, building engineer at the Geophysical Laboratory, retired in June after seventeen years.

At Embryology, Thomas Malooly, business manager for nineteen years, and Betty Phebus, accountant for sixteen years, retired this year. Embryology laboratory assistant Virgina Hicks, who gave twenty years of service to the department, and custodian Thomas Miller, who gave fifteen years, also retired at the end of the report year. At the Observatories, draftsperson Charles Hartwick retired after seven years of service.

Gains

Three new trustees were elected to the Carnegie Board in May: William F. Kieschnick, Gerald D. Laubach, and Sandra M. Faber. William F. Kieschnick, president and chief executive officer of the Atlantic Richfield Company, is currently a director of the American Federation for Aging Research, chairman of the board of the Museum of Contemporary Art, a fellow of the Aspen Institute for Humanistic studies, and a trustee of the California Institute of Technology. He is also on Rice University's Board of Governors and received in 1981 the University's Distinguished Alumni Award. (He graduated Phi Beta Kappa from Rice in 1947.) In 1981, Kieschnick was a member of the advisory committee of the White House Conference on Aging.

Gerald D. Laubach is president of Pfizer Inc. He joined the company in 1950 with a newly earned Ph.D. in organic chemistry from the Massachusetts Institute of Technology. Laubach is a director of

the CIGNA Corporation of Philadelphia, the Millipore Corporation of Bedford, Massachusetts, the National Association of Manufacturers, and the Pharmaceutical Manufacturers Association. He is a member of the Rockefeller University Council and of the Polytechnic Corporation Board. He recently served on the President's Commission on Industrial Competitiveness. He received the 1985 Palladium Medal from the Sociétié de Chimie Industrielle and a (New York) Mayor's Award for Science and Technology.

Sandra Faber, an astronomer and professor at the University of California's Lick Observatory, holds a B.S. from Swarthmore College, and a Ph.D. from Harvard University. From 1970 until 1971 she was a fellow at Carnegie's Department of Terrestrial Magnetism. She is a newly elected (1985) member of the National Academy of Sciences, a member of the National Science Foundation's astronomy advisory panel, and a member and former chair of the Visiting Committee to the Space Telescope Science Institute. In 1978 she received a Bart J. Bok prize. Last year, *Science Digest* named her as one of the 100 best American scientists under the age of 40. In 1986 she is slated to receive the Dannie Heineman Prize for Astrophysics from the American Astronomical Society and American Institute of Physics.

The Institution also gained five new staff members this year, two of them at the Department of Terrestrial Magnetism. John Graham earned his Ph.D. from the Australian National University. He has worked in both Galactic and extragalactic astronomy and is especially interested in problems of star formation. Before coming to Carnegie, he was for sixteen years an astronomer at the Cerro Tololo Inter-American Observatory in Chile. He is currently vice president of the American Astronomical Society.

Steven Shirey conducts trace-element and isotopic studies in investigations of the origin and evolution of the crust and mantle. He received his B.A. from Dartmouth, his M.S. from the University of Massachusetts, Amherst, and his Ph.D. (in geochemistry in 1984) from the State University of New York at Stony Brook. Shirey was a 1984 DTM research associate.

Steven McKnight, new staff member at the Department of Embryology, is interested in the signals that control protein-encoding genes of the herpes simplex virus. He received his Ph.D. from the University of Virginia and then spent four years (1977–1981) as a postdoctoral fellow and research associate at the Department of Embryology. Before returning to Carnegie as a staff member, he worked at the Hutchinson Cancer Research Center in Seattle.

Joining Carnegie's Department of Plant Biology as staff member this year is physiological ecologist Christopher Field. Field received his A.B. from Harvard and his Ph.D. from Stanford. Before coming to Carnegie, he spent three years as an assistant professor at the University of Utah. Field is currently conducting research in tropical rainforests of Mexico and China.

Gregory E. Muncill, a 1984 Geophysical Laboratory postdoctoral fellow, was appointed this year as the Laboratory's W. M. Keck Foundation Earth Sciences Research Scholar, a three-year position that was made possible by a grant from the W. M. Keck Foundation. Muncill earned his B.S. degree from the University of California, San Diego, and the Ph.D. from the Pennsylvania State University. He is particularly interested in the chemical evolution of igneous systems.

Two new appointments were made this year at the Institution's administrative offices. Cady Canapp joined the P Street staff as administrator for personnel and employee benefits, and Greg Silsbee was appointed grants administrator. Both positions are newly created.

Honors

The honors garnered each year by staff members, fellows, and former staff reflect years of hard work and dedication. This is well exemplified by the honor bestowed this year on Donald Brown, director of the Department of Embryology. On April 3, 1985, in a ceremony at Brandeis University, Brown received (with co-recipient Robert Letsinger of Northwestern University) the highly coveted Rosenstiel Medallion. Brown was cited for his pioneering work in understanding the development of an organism (the frog-like *Xenopus*) at the molecular level. A previous recipient of the Rosenstiel Medallion was Barbara McClintock.

Two staff members this year received prestigious awards from the National Academy of Sciences. W. Kent Ford of DTM received the James Craig Watson Medal for his work in the areas of image intensification and galactic dynamics, and Embryology staff member Allan Spradling, together with former staff member Gerald Rubin (now at the University of California, Berkeley), received the U. S. Steel Foundation Award in Molecular Genetics for developing a gene transfer technique in *Drosophila*. The three received their awards at a ceremony at the Academy on April 22, 1985.

George Wetherill, director of DTM, was doubly honored this year. In November 1984, he received the G. K. Gilbert Award of the Geological Society of America for distinguished contributions to planetary geology. In June 1985, he was awarded a University of Chicago Alumni Professional Achievement Citation.

Bjørn Mysen of the Geophysical Laboratory was elected a member of the Norwegian Academy of Science and Letters, a rare honor for an earth scientist. Mysen, a native of Norway, received the award in Oslo in May 1985.

Felix Chayes, another Geophysical staff member, received the Krumbein Medal of the International Association of Mathematical Geology during the November 1984 meeting of the Geological Society of America.

John Frantz of Geophysical was awarded a Carnegie–del Duca fellowship for 1985–1986. He is currently spending a year as a visiting researcher at the Centre de Recherches Pétrographiques et Géochemiques in Nancy, France.

A paper published in *Organic Geochemistry* by Geophysical Laboratory staff member Thomas Hoering was selected as Best Paper of the Year for 1984 by the Organic Geochemistry Division of the Geochemical Society.

Postdoctoral fellow Deidre Hunter of DTM was named the first Richard B. Roberts Fellow. She also received the 1984 Robert J. Trumpler Award from the Astronomical Society of the Pacific.

Observatories fellow Michael D. Gregg was awarded the 1985 Dirk Brouwer Memorial Prize by the Yale Astronomy Department.

Plant Biology postdoctoral fellow Terri Lomax received the P. F. Saunders Memorial Award from the American Society of Plant Physiologists. She was a 1984 NSF Postdoctoral Fellow in Plant Biology.

Former Department of Embryology staff member Elizabeth Ramsey was paid tribute in a *Hall of Fame* presentation at the American College of Obstetrics and Gynecology's 33rd annual clinical meeting in Washington, D.C.

Former Plant Biology fellow Jeffrey Palmer, now at the University of Michigan, received a Presidential Young Investigator Award.

John Ferry, former fellow at the Geophysical Lab and now at Johns Hopkins University, received the Mineralogical Society of America Award for 1985.

Margaret L. A. MacVicar, the Institution's vice president, received an honorary degree from Clarkson University in May.

In October 1984, William R. Hewlett received the Heald Award from the Illinois Institute of Technology. In February 1985, he received an honorary doctoral degree from The Johns Hopkins University. Also in February, he received a National Medal of Science from President Reagan.

Edward E. David also received three awards this year: the Scientist of the Year Award from *Research and Development* magazine in September, the Arthur M. Bueche Medal from the National Academy of Engineering in October 1984, and the Delmer S. Fahrney Medal from the Franklin Institute in April 1985.

Crawford Greenewalt was reelected president of the American Philosophical Society in April 1985. Edward E. David and William Golden were elected councillors.

Frank Stanton received the first Walter Cronkite Award for Excellence in Journalism and Telecommunication from Arizona State University on October 5, 1984. In June 1985 he received an honorary doctor of laws degree from Harvard University.

For his book *Making the Future Work*, John Diebold received the 1985 George Washington Medal for Excellence (book category) from the Freedom Foundation.

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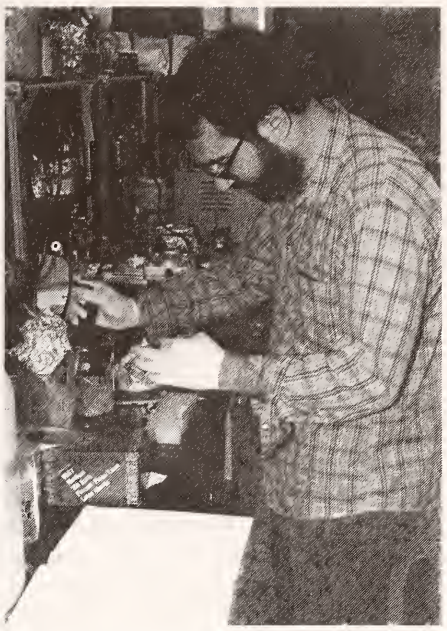

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George W. Preston

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Stephen A. Shectman

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Thomas Y. Steiman-Cameron

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Peter B. Stetson

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Fisheye-lens view taken on the occasion of the replacement of the wooden catwalk on the 150-foot solar tower telescope at Mount Wilson. Seen at the center is the 2.5-meter Hooker telescope. Shown: Dave Carr and Tony Misch. Photo by Steve Padilla.

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Ian B. Thompson

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ADMINISTRATION

James D. Ebert

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Carnegie Institution of Washington Year Book 83, *viii* + 187 pages, 39 illustrations, December 1984.

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[1]From September 1, 1984
[2]From August 1, 1984
[3]From September 17, 1984
[4]From November 1, 1984
[5]To August 31, 1984
[6]To May 10, 1985
[7]To October 31, 1984
[8]From December 1, 1984
[9]To July 31, 1984
[10]To December 1, 1984
[11]From October 1, 1984
[12]From February 4, 1985
[13]From January 31, 1985
[14]From January 31 to May 31, 1985
[15]To March 1, 1985
[16]From February 1, 1985
[17]To May 17, 1985
[18]To October 23, 1984
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[1]To December 4, 1984
[2]To August 30, 1984
[3]To December 26, 1984
[4]To January 1, 1985
[5]To August 15, 1984
[6]To December 31, 1984
[7]To September 30, 1984
[8]To September 28, 1984
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[12]To April 23, 1985
[13]To February 28, 1985
[14]To January 31, 1985
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[4]To July 31, 1984
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[6]To December 19, 1984
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[13]From August 28, 1984
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[15]From December 3, 1984
[16]From September 10, 1984
[17]From September 1, 1984
[18]From May 9, 1985
[19]From November 19, 1984
[20]Temporary employee
[21]Retired, June 30, 1985
[22]Resigned, October 29, 1984
[23]Resigned, May 17, 1985
[24]From May 1, 1985
[25]To January 31, 1985
[26]From May 8, 1985

GEOPHYSICAL LABORATORY

Research Staff

Peter M. Bell
Francis R. Boyd, Jr.
Felix Chayes
Marilyn L. F. Estep
Larry W. Finger
John D. Frantz
Kenneth A. Goettel[1]
P. Edgar Hare
Robert M. Hazen
Thomas C. Hoering
T. Neil Irvine
Ikuo Kushiro[2]
Ho-kwang Mao
Bjørn Mysen
Douglas Rumble III[3]
David Virgo
Hatten S. Yoder, Jr., Director

Keck Earth Sciences Research Scholar

Gregory E. Muncill[4]

Research Associates

Andrew Y. Au[5]
Martha W. Schaefer[6]
Ji-an Xu[7]

Postdoctoral Fellows

Donald B. Dingwell[8]
Andrew P. Giże
Russell J. Hemley[8]
Anne M. Hofmeister[9]
Pascal Richet[10]
Daniel J. Schulze[11]
Thomas W. Stafford, Jr.[12]

Predoctoral Fellows

Andrew P. Jephcoat, Johns Hopkins University[6]
L. A. Cifuentes, University of Delaware[13]

Research Assistant

Norma K. Pannell, George Washington University[14]

Supporting Staff

Andrew J. Antoszyk, Instrument Maker
Charlie A. Batten, Shop Foreman and Instrument Maker
Stephen D. Coley, Sr., Machinist
Roy R. Dingus, Instrument Maker[15]
Mack C. Ferguson, Jr., Custodian
David J. George, Electronics Technician

Christos Hadidiacos, Electronics Engineer
Marjorie E. Imlay, Assistant to the Director[16]
Michael Jenkins, Secretary-Receptionist[17]
Lavonne Lela, Librarian-Stenographer[18]
Harvey J. Lutz, Clerk and Technician
Mabel B. Mattingly, Stenographer
Harvey L. Moore, Building Engineer[19]
Lawrence B. Patrick, Custodial Supervisor
Dolores M. Petry, Editor and Librarian
David Ratliff, Jr., Custodian and Thin-Section Technician
A. David Singer, Executive Officer[20]
John A. Straub, Accountant

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[1]To August 31, 1984
[2]Leave of absence, University of Tokyo
[3]To June 30, 1985. Leave of absence for temporary service at National Science Foundation
[4]Postdoctoral Fellow to January 31, 1985
[5]Postdoctoral Fellow to September 30, 1984
[6]To June 30, 1985
[7]To February 28, 1985
[8]From September 1, 1984
[9]Research Associate to October 15, 1984
[10]To June 30, 1984
[11]To September 30, 1984. Position as Assistant Professor at Queen's University, Ontario
[12]From September 1, 1984
[13]From July 1, 1984
[14]To April 30, 1985
[15]From December 10, 1984
[16]Stenographer to March 31, 1985
[17]From May 16, 1985
[18]From April 1, 1985
[19]Retired, June 30, 1985
[20]Died, March 13, 1985

MOUNT WILSON AND LAS CAMPANAS OBSERVATORIES

Research Staff

Halton C. Arp[1]
Alan Dressler
Robert F. Howard[2]
Jerome Kristian
S. Eric Persson
George W. Preston, Director
Allan Sandage
Paul L. Schechter
Leonard Searle
Stephen A. Shectman
Horace W. Babcock, Emeritus
Olin C. Wilson, Emeritus

Adjunct Staff Members

W. Kent Ford, Jr., Department of Terrestrial Magnetism, CIW
Vera C. Rubin, Department of Terrestrial Magnetism, CIW
François Schweizer, Department of Terrestrial Magnetism, CIW

Las Campanas Resident Scientists

Wojciech A. Krzeminski, Resident Scientist
William E. Kunkel, Resident Scientist/Administrator

Staff Associate

Arthur H. Vaughan, Perkin-Elmer Corporation

Research Associates

Todd A. Boroson[3]
Gary Chapman[4]
Douglas K. Duncan
Ian B. Thompson

Postdoctoral Research Fellows

David H. Bruning[5]
Belva G. Campbell[6]
Michael D. Gregg, Carnegie Fellow[7]
Wendy L. Freedman, Carnegie Fellow[7]
Edmond Giraud, Carnegie–del Duca Fellow[7]
Robert I. Jedrzejewski, U.K. SERC Fellow[8]
Geoffrey W. Marcy, Carnegie Fellow[9]
Herschel B. Snodgrass[10]
Thomas Y. Steiman-Cameron, Carnegie Fellow
Nicholas B. Suntzeff, Carnegie Las Campanas Observatory Fellow
Rogier A. Windhorst, Carnegie Fellow

Predoctoral Carnegie-Chile Research Fellow

Fernando J. Selman, California Institute of Technology

Sabbatical Visitors

Eduardo Hardy, University Laval, Canada[11]
Sister Mary Matthew Baltus, Mercyhurst College[12]

Visiting Associates

Gerard Gilmore, University of Cambridge[13]
Rita E. M. Griffin, University of Cambridge[13]
Roger F. Griffin, University of Cambridge[13]
Gustav A. Tammann, University of Basel, Switzerland[13]

Supporting Staff, Pasadena

John M. Adkins, Senior Research Assistant, Solar Physics
Maria Anderson, Manuscript Typist and Editor
John R. Bedke, Photographer[13]
Nicolette Breski, Purchasing Agent
Richard T. Black, Business Manager
John E. Boyden, Systems Programmer, Solar Physics
Ken D. Clardy, Data Systems Manager
Maynard K. Clark, Electronics Engineer, Solar Physics
Harvey W. Crist, Machinist
Gary Fouts, Research Assistant/Observer[14]
Carroll L. Friswold, Head, Design Group
Joan Gantz, Librarian
Robert T. Georgen, Foreman, Machine Shop
Pamela I. Gilman, Research Assistant, Solar Physics
Rhea M. Goodwin, Assistant to the Director
Charles E. Hartrick, Draftsperson[15]
Basil N. Katem, Senior Research Assistant
Stephen P. Padilla, Research Assistant, Solar Physics
Frank Perez, Technical Assistant to the Director[16]
Christopher K. Price, Electronics Engineer
Stephen L. Knapp, Electronics Engineer
William D. Qualls, Driver
Delores B. Sahlin, Receptionist
Edward H. Snoddy, Designer
Jeannie M. Todd, Bookkeeper
Estuardo Vasquez, Machinist
Stephen Wilson, Carpenter
Laura A. Woodard, Research Assistant/Observer

Supporting Staff, Mount Wilson

David M. Carr, Mountain Superintendent[16]
Judy L. Carr, Stewardess (part-time)[17]
James Frazer, Night Assistant/Observer
Ricardo de Leon, Steward
Howard H. Lanning, Night Assistant/Observer[14]
Jean Mueller, Night Assistant/Observer
Anthony Misch, Observatory Technician
Donald R. Poppe, Night Assistant/Observer[18]
Eric Rawe, Observatory Technician
Michael Thornberry, Steward[19]
Larry Webster, Resident Solar Observer

Supporting Staff, Las Campanas

Hector Balbontín I., Chef
Angel Cortés L., Accountant
Oscar Duhalde C., Night Assistant
Angel Guerra F., Night Assistant
Leonel Lillo A., Carpenter
Mario Mondaca O., El Pino Guard
Herman Olivares G., Warehouse Attendant
Ljubomir Papič P., Mountain Superintendent
Alfredo Paredes Z., Equipment Operator
Fernando Peralta B., Night Assistant
Leonardo Peralta B., Driver and Purchaser
Victorino Riquelme P., Janitor
Honorio Rojas P., Pump Operator
Pedro Rojas T., Mason
William Robinson W., Electronic Technician
Luis Hernán Solis P., Electronic Technician
Mario Taquias L., Plumber
Gabriel Tolmo V., El Pino Guard
Jorge Tolmo V., El Pino Guard
Mauricio Villalobos, Chef
Patricia Villar B., Administrative Assistant
Victor Valenzuela L., Mechanic[7]
Alberto Zuniga A.

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[1]On leave of absence, Max Planck Institute for Physics and Astrophysics
[2]To July 31, 1984
[3]To October 31, 1984
[4]From September 1, 1984 to June 30, 1985
[5]To July 30, 1984
[6]From December 1, 1984
[7]From September 1, 1984
[8]From March 18, 1985
[9]To August 31, 1984
[10]To July 31, 1984
[11]To December 31, 1984
[12]From January 1 to June 1, 1985
[13]To June 30, 1985
[14]To December 31, 1984
[15]Retired, June 30, 1985
[16]From July 1, 1984
[17]From April 1, 1985
[18]From January 23, 1985
[19]To March 31, 1985

APPOINTMENTS IN SPECIAL SUBJECT AREAS

Roy J. Britten, Staff Member of the Institution[1]

Barbara McClintock, Distinguished Service Member of the Institution[2]

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[1]Distinguished Carnegie Senior Research Associate, Developmental Biology Research Group, California Institute of Technology
[2]Cold Spring Harbor, New York

OFFICE OF ADMINISTRATION

Lloyd H. Allen, Custodian
Ray Bowers, Editor, Publications Officer
Don A. Brooks, Custodian
Cady Canapp, Personnel/Employee Benefits Administrator[1]
Carolyn J. Davis, Secretary
Barbara F. Deal, Administrative Assistant
D'Ann L. DeBruyn, Secretary[2]
James D. Ebert, President
Jacqueline Green, Secretary to the President[3]
Joseph M. S. Haraburda, Accounting Manager
Susan E. Henderson, Systems Accountant[4]
Jill Humphreys, Receptionist and Clerk[5]
Antoinette M. Jackson, Facilities and Support Services Manager
Sherman L. E. Johnson, Payroll Supervisor
Jacqueline L. King, Administrative Assistant[5]
Richard S. Kuzmyak, Systems Accountant[6]
John C. Lawrence, Controller[8]
Margaret L. Loflin, Secretary to the Vice President
Margaret L. A. MacVicar, Vice President
John B. Osolnick, Accountant[4]
Patricia Parratt, Assistant Editor
Arnold J. Pryor, Equal Opportunity Officer
Richard B. Sell, Accountant[9]
Greg Silsbee, Grants and Contracts Administrator[10]
Susan Y. Vasquez, Assistant to the President

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[1]From August 27, 1984
[2]To November 15, 1984
[3]From December 10, 1984
[4]Junior Accountant to January 3, 1985
[5]From October 8, 1984
[6]To August 31, 1984
[7]To February 25, 1985
[8]Title changed from Bursar, May 2, 1985
[9]From February 11, 1985
[10]From April 15, 1985

Visiting Investigators

DEPARTMENT OF PLANT BIOLOGY

Marilyn Estep, Geophysical Laboratory, CIW
Robert Guy, University of Calgary, Alberta
Brian Jordan, Glasshouse Crops, West Sussex, England (NATO)
Jacob Levitt, Senior Fellow, University of Minnesota
W. Patrick Williams, Senior Lecturer, Biophysics Department, Chelsea College, University of London

DEPARTMENT OF TERRESTRIAL MAGNETISM

Barbara Barreiro, Dartmouth College, New Hampshire
Paul Dysart, Virginia Polytechnic Institute and State University
Wang Enfu, State Seismological Bureau, Beijing, People's Republic of China
Dale W. Evertson, University of Texas, Austin
Jiang Guang, State Seismological Bureau, Beijing, People's Republic of China
William K. Hart, Miami University, Ohio
Liu Lanbo, State Seismological Bureau, Beijing, People's Republic of China
Milan J. Pavich, U. S. Geological Survey, Reston, Virginia
J. Arthur Snoke, Virginia Polytechnic Institute and State University
Richard T. Williams, University of South Carolina, Columbia

GEOPHYSICAL LABORATORY

Jagan Akella, Lawrence Livermore Laboratories
Mary Jo Baedecker, U. S. Geological Survey
Mark Barton, University of California, Los Angeles
Lukas Baumgartner, University of Basel, Switzerland
Nabil Z. Boctor, Purdue University
Luis A. Cifuentes, University of Delaware
A. A. Finnerty, University of California, Davis
Hiroyuki Fukuyama, University of Tokyo[1]
Fred Gallaraga, University of Maryland
Ronald W. L. Kimber, CSIRO, Adelaide, Australia
Julie Kokis, George Washington University
Vince La Piana, Yale University
Barbara Levinson, University of Maryland
Heinz A. Lowenstam, California Institute of Technology
Ian D. MacGregor, National Science Foundation
Vivek Navale, University of Maryland
Elliot Spiker, U. S. Geological Survey
E. Kent Sprague, University of Georgia
Jianguo Xu, Institute of Geochemistry, Academia Sinica, People's Republic of China

[1]Died, August 10, 1984

MOUNT WILSON AND LAS CAMPANAS OBSERVATORIES

Marc Aaronson, University of Arizona
Thomas Albert, University of Basel
Ferdinand Baas, University of Leiden
Pierre Bergeron, University of Montreal
Ben Bischoff, Oberlin College
Todd Boroson, University of Michigan
Edward Brugel, University of Colorado
Andrew Buffington, University of California, San Diego
Paul Butler, San Francisco State University
A. Cacciani, Jet Propulsion Laboratory
Nelson Caldwell, Cerro Tololo Inter-American Observatory
Luzius Cameron, University of Basel
Luis Campusano, University of Chile
J. Close, Jet Propulsion Laboratory
Marc Colavita, Massachusetts Institute of Technology
Marc Davis, University of California, Berkeley
Serge Demers, University of Montreal
P. Dumont, Jet Propulsion Laboratory
Stephen Elmore, U. S. Naval Research Laboratory
Alexei Filippenko, University of California, Berkeley
Gilles Fontaine, University of Montreal
Otto Franz, Lowell Observatory
Alfred Gautschy, University of Basel
Richard Gomer, University of California, San Diego
Thomas Graves, U. S. Naval Research Laboratory

F. Greenberg, Jet Propulsion Laboratory
Hugh Harris, Lowell Observatory
John Hershey, U. S. Naval Observatory
Keith Horne, University of Cambridge
D. J. Hutter, Georgia State University
James Imamura, Los Alamos National Laboratory
Renee Kraan-Korteweg, University of Basel
Richard Kron, University of Chicago
Jeff Kuhn, Princeton University
Lukas Labhardt, University of Basel
S. Lasseter, Georgia State University
Bruno Leibundgut, University of Basel
Victoria Lindsay, San Francisco State University
Carol Lonsdale, Jet Propulsion Laboratory
Craig Mackay, University of Cambridge
Barry Madore, University of Toronto
Geoffrey W. Marcy, San Francisco State University
Christopher McAlary, University of Arizona
Harold McAlister, Georgia State University
A. Meiksin, University of California, Berkeley
Jorge Melnick, University of Chile
Mariano Moles, University of Andalucia
Peter Nisensen, Harvard-Smithsonian Center for Astrophysics
Robert W. Noyes, Harvard-Smithsonian Center for Astrophysics
John Ottusch, University of California, Berkeley
Neil Reid, University of Sussex
E. Rhodes, University of Southern California and Jet Propulsion Laboratory
Douglas O. Richstone, University of Michigan
Michael Shao, Harvard-Smithsonian Center for Astrophysics
Jeff Shapiro, University of Southern California/Rhodes
Michael Shara, Space Telescope Science Institute
R. Simon, U. S. Naval Research Laboratory
Bradford Smith, University of Arizona
Horace Smith, Michigan State University
Verne Smith, University of Texas
Joseph Snider, Oberlin College
Andreas Spaenhauer, University of Basel
Robert Stachnik, Harvard-Smithsonian Center for Astrophysics
Rae Stiening, Stanford University
Linda Stryker, Department of Terrestrial Magnetism, CIW
J. P. Swings, University of Liège
J. Surdej, European Southern Observatory
Santiago Tapia, University of Arizona
Roberto Terlevich, University of Cambridge
Richard Terrile, Jet Propulsion Laboratory
A. Thierry, Jet Propulsion Laboratory
Carlos Torres, University of Chile
Ken-ichi Wakamatsu, Gifu University
Douglas Welch, University of Toronto
Karen Wilson, San Francisco State University
Rosemary Wyse, University of California, Berkeley
Janet Yamanaka, Yale University
Alma Zook, Pomona College

California Institute of Technology Observers

Mary Barsony
Timothy Beers
Gregory Bothun
Judith Cohen
Christopher Impey
Ken Libbrecht
Barry F. Madore
Jeremy Mould
James Nemec
Alain Porter
R.. Michael Rich
Wallace L. W. Sargent
John Trauger
David Tytler

Report of the Executive Committee

To the Trustees of the Carnegie Institution of Washington

In accordance with the provisions of the By-Laws, the Executive Committee submits this report to the Annual Meeting of the Board of Trustees.

During the fiscal year ending June 30, 1985, the Executive Committee held four meetings. Accounts of these meetings have been or will be mailed to each Trustee.

A full statement of the finances and work of the Institution for the fiscal year ended June 30, 1984, appears in the Institution's *Year Book 83*, a copy of which has been sent to each Trustee. An estimate of the Institution's expenditures in the fiscal year ending June 30, 1986, appears in the budget recommended by the Committee for approval by the Board of Trustees.

The terms of the following members of the Board expire on May 3, 1985:

William T. Coleman, Jr.
Edward E. David, Jr.
William T. Golden
Richard E. Heckert
Antonia Ax:son Johnson
Robert M. Pennoyer
Robert C. Seamans, Jr.

In addition, the terms of office of the Vice-Chairman and Secretary of the Board, all Committee Chairmen, and the following members of Committees expire on May 3, 1985:

Finance Committee
William T. Golden

Auditing Committee
Philip H. Abelson

Nominating Committee
Robert G. Goelet

Robert C. Seamans, Jr., *Chairman*

May 3, 1985

Abstract of Minutes

of the Eighty-Eighth Meeting of the Board of Trustees

The annual meeting of the Board of Trustees was held in the Board Room of the Administration Building on Friday, May 3, 1985. The meeting was called to order by Chairman William R. Hewlett.

The following Trustees were present: Philip H. Abelson, Lewis M. Branscomb, William T. Coleman, Jr., John Diebold, William T. Golden, William C. Greenough, Caryl P. Haskins, Richard E. Heckert, William R. Hewlett, Antonia Ax:son Johnson, John D. Macomber, Robert M. Pennoyer, Richard S. Perkins, Robert C. Seamans, Jr., Frank Stanton, Charles H. Townes, and Sidney J. Weinberg, Jr. Also present were James D. Ebert, President, Margaret L. A. MacVicar, Vice President, John C. Lawrence, Controller, Susan Y. Vasquez, Assistant Secretary, and Marshall Hornblower, Counsel.

The minutes of the Eighty-Seventh Meeting were approved.

The reports of the Executive Committee, the Finance Committee, the Employee Benefits Committee, and the Auditing Committee were accepted. On the recommendation of the latter, it was resolved that Price Waterhouse & Co. be appointed as public accountants for the fiscal year ending June 30, 1986.

Sections 1.2, 1.5, the heading of Article III, and Sections 3.2, 3.3, and 3.4 of the By-Laws were amended. The amended language is given in the By-Laws printed on pages 187–192 of this Year Book.

On the recommendation of the Nominating Committee, Sandra M. Faber, William F. Kieschnick, and Gerald D. Laubach were elected members of the Board of Trustees, and the following were reelected for terms ending in 1988: William T. Coleman, Jr., Edward E. David, Jr., William T. Golden, Richard E. Heckert, Antonia Ax:son Johnson, Robert M. Pennoyer, and Robert C. Seamans, Jr.

Richard E. Heckert was elected Vice-Chairman of the Board and William T. Golden was elected Secretary of the Board, both for terms ending in 1988.

The following were elected for one-year terms: Robert C. Seamans, Jr., as Chairman of the Executive Committee; Sidney J. Weinberg, Jr., as Chairman of the Finance Committee; Robert M. Pennoyer, as Chairman of the Auditing Committee; Antonia Ax:son Johnson, as Chairman of the Nominating Committee; and William T. Coleman, Jr., as Chairman of the Employee Benefits Committee.

Vacancies in the Standing Committees, with terms ending in 1988, were filled as follows: William T. Golden was elected a member of the Finance Committee, and Edward E. David, Jr., was elected a member of the Nominating Committee. In addition, Lewis M. Branscomb was elected a member of the Executive Committee for the unexpired term ending in 1987, William C. Greenough was elected a member of the Executive Committee for the unexpired term ending in 1986, and Robert M. Pennoyer and Philip H. Abelson were elected members of the Auditing Committee for the unexpired terms

ending in 1987.

The Chairman pointed out that Dr. Stanton, who had been an active member of the Board for 22 years, serving as Chairman from 1977 to 1979, had decided to resign. This resignation was noted with regret, and in accordance with Section 1.6 of the By-Laws, Dr. Stanton was designated Trustee Emeritus.

The following resolutions were approved:

Resolved that, because of the desirability of locating the Institution's programs in the Geophysical Laboratory and the Department of Terrestrial Magnetism onto a common site, the Institution proceed with plans for new or remodeled buildings for the departments at a single site and that the sum of $250,000 be set aside from reserve funds for architectural fees, enabling completion of the preliminary design phase contingent upon the determination of the site.

Resolved that, in recruiting a new Director of Geophysical Laboratory (to succeed Hatten Yoder, who will retire on June 30, 1986), the Institution seek an individual who is prepared to work with George Wetherill, Director of the Department of Terrestrial Magnetism, and with President James Ebert and his successor in effecting the move to a common site with the expectation of consolidation of the two departments.

Resolved that the Institution undertake a capital campaign for the earth and planetary sciences facilities.

Resolved that the Institution take the steps necessary to ensure its participation in a large new telescope, intending to commit by 1989 not less than $10 million toward the construction of a large telescope (8-meter) at Las Campanas, provided that engineering studies and site surveys, to be undertaken during 1985–1989, demonstrate its feasibility, and provided that agreements can be completed with the University of Arizona and, if appropriate, an additional partner.

Resolved that, in recruiting a new Director of The Observatories (to succeed George Preston, whose term expires on June 30, 1986), the Institution search with the expectation of undertaking development of the new telescope.

Resolved that the Institution undertake a campaign to increase its endowment by $25 million.

The annual report of the President was accepted.

To provide for the operation of the Institution for the fiscal year ending June 30, 1986, and upon recommendation of the Executive Committee, the sum of $15,800,000 was appropriated.

Financial Statements

for the year ended June 30, 1985

Carnegie Institution of Washington
Ten-Year Financial Summary, 1976–1985
(All figures are thousands of dollars; fiscal years ended June 30)

	1985	1984	1983	1982	1981	1980	1979	1978	1977	1976
Revenues										
Interest and dividends	$11,196	$10,224	$ 8,983	$9,100	$6,976	$6,486	$5,256	$5,019	$4,675	$3,958
Other	163	187	241	314	197	156	306	80	338	126
Restricted grants, expended	5,198	4,308	4,476	4,587	3,912	2,613	1,805	1,544	1,077	772
Total income	16,557	14,719	13,700	14,001	11,085	9,255	7,367	6,643	6,090	4,856
Expenses										
Terrestrial Magnetism	1,598	1,563	1,513	1,478	1,212	1,030	1,000	1,106	1,209	1,046
Mount Wilson and Las Campanas Observatories	3,022	2,831	2,473	2,648	1,960	2,000	1,983	1,868	2,260	2,838
Geophysical Laboratory	1,674	1,506	1,412	1,745	1,168	1,269	1,284	1,202	1,162	1,032
Embryology	937	864	810	343	77	483	815	818	900	816
Plant Biology	1,414	1,078	820	703	614	602	537	530	636	620
Research projects, etc.	55	58	67	96	76	118	190	107	115	111
Office of Administration	1,242	1,196	1,099	1,073	941	791	710	602	577	500
General publications	63	80	67	76	91	66	62	78	59	66
Professional fees, insurance, taxes	208	327	311	264	231	199	175	216	226	158
Retiree and special benefits	202	203	156	190	192	139	143	145	117	102
Investment services	389	411	395	385	342	278	308	265	238	205
Restricted grants, expended	5,198	4,308	4,476	4,587	3,912	2,613	1,805	1,544	1,077	772
Total expenses	16,002	14,425	13,599	13,588	10,816	9,589	9,012	8,481	8,576	8,266
Excess (deficiency) of revenues over expenses before capital changes	$ 555	$ 294	$ 101	$ 413	$ 269	$ (334)	$(1,645)	$(1,838)	$(2,486)	$(3,410)
Realized net gain (loss) on investments	$ 8,066	$11,707	$16,157	$6,774	$5,350	$4,581	$1,752	$ (102)	$2,803	$4,365
Gifts—endowment and special funds	1,114	809	1,097	1,028	364	157	998	637	241	41
Market value of investments	153,210	130,805	137,859	95,759	101,464	94,359	86,425	84,136	89,287	92,215

Contributions, Gifts, and Grants for the Year Ended June 30, 1985

Jagannadham Akella
Joseph F. Albright
American Cancer society
Anonymous
Toshi Asada
BARD (United States–Israel Agriculture Foundation)
Clifton Batson
Ailene J. Bauer
Liselotte Beach
Giuseppe Bertani
Earle B. Biesecker
John J. Bonica
Montgomery S. Bradley
Bristol-Myers Co.
Donald D. Brown
Donald M. Burt
William Buscombe
California Institute of Technology
Carnegie Corporation of New York
James F. Case
Ernst W. Caspari
Celanese Corporation
Britton Chance
People's Republic of China
The Jane Coffin Childs Memorial Foundation
John and Annette Coleman
Charles E. Culpeper Foundation, Inc.
Howard Clark Dalton
The Charles A. Dana Foundation, Inc.
Robert L. DeHaan
Louis E. DeLanney
John Diebold
Bruce R. Doe
Martin W. Donner
E. I. Du Pont de Nemours
James and Alma Ebert
Frank and Margaret Edmondson
W. G. Ernst
Exxon Education Foundation
Sandra M. Faber
Dorothy Ruth Fischer
Michael Fleischer
Louis Flexner
W. Kent Ford
C. S. French
Alberto Giesecke
Robert Goelet
Sibyl and William T. Golden Foundation
Crawford and Margaretta Greenewalt
Gilbert S. Greenwald
Sam A. Haroz, II
Caryl P. and Edna Haskins
Richard E. Heckert
Mary G. Hedger
H. Lawrence Helfer
Edward P. Henderson
Alfred D. Hershey
William R. Hewlett
William M. Hiesey
F. Earl Ingerson
International Business Machines Corp.
George F. Jewett, Jr.
The Johns Hopkins University
Antonia Ax:son Johnson
Paul A. Johnson
W. M. Keck Foundation
Mac L. Keith
Robert B. King
Elizabeth Ramsey and Hans A. Klagsbrunn
Robert N. Kreidler
Ikuo Kushiro
Arthur and Faith La Velle
A. H. Lawrence
Harold H. Lee
Ta-Yan Leong
Edna G. Lichtenstein
Melvyn Lieberman
John D. & Catherine T. MacArthur Foundation
John D. Macomber
Horace N. Marvin
Sheila McCormick
The Andrew W. Mellon Foundation
Günter Moh
Ambrose Monell Foundation
Monsanto Company
Francis L. Moseley
Muscular Dystrophy Association
Howard R. Naslund
National Aeronautics and Space Administration
National Geographic Society
National Science Foundation
Office of Naval Research
University of Nevada
Malcolm A. Nobs
Jessie Smith Noyes Foundation, Inc.
Tokindo Okada
Lucy C. Paschal
Robert M. Pennoyer
The Penta Corporation
The Pew Memorial Trust
Pioneer Hi-Bred International, Inc.
Public Health Service
Peter H. Quail
P. R. Ranganayaki
Peter Raven
Curt P. Richter
Josephine Roberts
Robert G. Roeder
Glenn C. Rosenquist

(continued)

Contributions, Gifts, and Grants for the Year Ended June 30, 1985 (continued)

Dorothea Rudnick
Bruce C. Rule
Damon Runyon–Walter Winchell Cancer Fund
Paul A. Scherer
Maarten and Corrie Schmidt
Robert C. Seamans, Jr.
Shell Companies Foundation, Inc.
Alfred P. Sloan Foundation
A. Ledyard Smith
Harold Speert
Frank Stanton
Roger D. Sumner
Yoshiaki Suzuki
Ikuo Takeuchi
The Teagle Foundation, Inc.
Heinz Tiedemann
George R. Tilton
Charles H. Townes
United Agriseeds
United States Agency for International Development
United States Department of Agriculture
United States Department of Commerce
United States Department of Energy
United States Department of the Interior
University of California
A. Unsoeld
William B. Upholt
Larry N. Vanderhoef
Arthur H. Vaughan
George Wallerstein
Sidney J. Weinberg, Jr.
Wenner-Gren Foundation
Richard E. White
W. Dexter Whitehead, Jr.
Helen Hay Whitney Foundation
David Gayle Whittingham
P. Frank Winkler
Frederick T. Wolf
Violet K. Young

Price Waterhouse

1801 K STREET, N.W
WASHINGTON, DC 20006
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September 5, 1985

To the Auditing Committee of the
Carnegie Institution of Washington

In our opinion, the accompanying statements of assets, liabilities and fund balances and the related statements of revenue, expenses, and changes in fund balances present fairly the financial position of the Carnegie Institution of Washington at June 30, 1985 and 1984, and the results of its operations and the changes in its fund balances for the years then ended, in conformity with generally accepted accounting principles consistently applied. Our examinations of these statements were made in accordance with generally accepted auditing standards and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

Our examinations were made for the purpose of forming an opinion on the basic financial statements taken as a whole. The supporting schedules 1 through 5 are presented for purposes of additional analysis and are not a required part of the basic financial statements. Such information has been subjected to the auditing procedures applied in the examination of the basic financial statements and, in our opinion, is fairly stated in all material respects in relation to the basic financial statements taken as a whole.

Price Waterhouse

STATEMENTS OF ASSETS, LIABILITIES, AND FUND BALANCES
JUNE 30, 1985 AND 1984

	1985	1984
ASSETS		
Current assets		
Cash and cash equivalents	$ 3,975,889	$ 519,851
Accounts receivable and advances	76,668	116,942
Grants receivable	393,639	339,209
Accrued interest and dividends	971,643	910,906
Due from brokers	649,040	...
Total current assets	6,066,879	1,886,908
Investments*		
Fixed income—short term	2,764,000	51,223,621
Fixed income—bonds	27,570,290	12,034,596
Fixed income—mortgages	20,616,770	22,969,328
Corporate stocks	84,176,749	44,668,237
Other	548,559	451,875
Adjustment to lower of cost or market	...	(542,276)
Total investments	135,676,368	130,805,381
Plant		
Land	1,019,524	1,027,524
Buildings	4,369,812	4,051,744
Equipment	10,218,544	10,211,819
Total plant	15,607,880	15,291,087
Total assets	$157,351,127	$147,983,376
LIABILITIES AND FUND BALANCES		
Current liabilities		
Due to brokers	...	2,692,583
Accounts payable and accrued expenses	1,204,541	965,319
Deferred grant income	2,411,213	1,610,448
Total current liabilities	3,615,754	5,268,350
Fund balances	153,735,373	142,715,026
Total liabilities and fund balances	$157,351,127	$147,983,376

* Approximate market value on June 30, 1985: $153,210,227; June 30, 1984: $130,805,381.

The accompanying notes are an integral part of these statements.

STATEMENTS OF REVENUES, EXPENSES, AND CHANGES IN FUND BALANCES FOR THE YEARS ENDED JUNE 30, 1985 AND 1984

	Year Ended June 30	
	1985	1984
Revenues		
Investment income	$ 11,196,173	$ 10,224,014
Grants		
Federal	4,156,462	3,370,722
Private	1,042,142	936,811
Other income	162,933	187,423
Total revenues	16,557,710	14,718,970
Expenses		
Personnel and related	9,296,744	8,745,860
Equipment	1,880,666	1,290,621
General	4,825,015	4,388,688
Total expenses	16,002,425	14,425,169
Excess of revenues over expenses before capital changes	555,285	293,801
Capital changes		
Realized net gain on investments	8,066,121	11,707,307
Unrealized gain (loss) on investments	542,276	(542,276)
Gifts—endowment and special funds	1,113,859	809,357
Land, buildings, and equipment capitalized	316,793	9,942
Sale of property	426,013	...
Total capital changes	10,465,062	11,984,330
Excess of revenues and capital changes over expenses	11,020,347	12,278,131
Funds balance, beginning of year	142,715,026	130,436,895
Funds balance, end of year	$153,735,373	$142,715,026

The accompanying notes are an integral part of these statements.

Notes to the Financial Statements
June 30, 1985

Note 1. Significant Accounting Policies

The financial statements of the Institution are prepared on the accrual basis of accounting.

Investments are carried on the balance sheet in the aggregate at the lower of cost or market value. A detailed listing of all securities held by the Institution as of June 30, 1985 has been included as Schedule 5 of this report.

The Institution capitalizes expenditures for land, buildings, telescopes and other significant equipment, and construction projects in progress. Expenditures for other equipment are charged to current operations as incurred, and the cost of such other equipment is not capitalized. The Institution follows the policy of not depreciating its buildings and its telescopes and other significant equipment.

Note 2. Retirement Plan

The Institution has a noncontributory money-purchase retirement plan in which all United States personnel are eligible to participate. Voluntary contributions may also be made by employees. Actuarially determined contributions are funded currently by the Institution, and there are no unfunded past service costs. The total contributions made by the Institution were $833,113 in 1985 and $845,671 in 1984. Benefits under the plan upon retirement depend upon the investment performance of the Institution's Retirement Trust. After four years' participation (one year's participation beginning July 1, 1984), an individual's benefits are fully vested.

Note 3. Restricted Grants

Restricted Grants are funds received from foundations, individuals, and federal agencies in support of scientific research and educational programs. The Institution follows the policy of reporting revenues only to the extent that reimburseable expenditures are incurred. The Restricted Grants Statement (Schedule 3) shows all current grants.

Note 4. Income Taxes

The Instititution is exempt from federal income tax under Section 501(c)(3) of the Internal Revenue Code. Accordingly, no provision for income taxes is reflected in the accompanying financial statements. The Institution is also an educational institution within the meaning of Section 170(b)(1)(A)(ii) of the Code. The Internal Revenue Service has classified the Institution as other than a private foundation, as defined in Section 509(a) of the Code.

SCHEDULE OF EXPENSES BY DEPARTMENT FOR THE YEARS ENDED JUNE 30, 1985 AND 1984

	1985				1984
	Endowment and Special	Restricted Grants Federal	Restricted Grants Private	Total Expenses	Total Expenses
Education and scientific research expenses					
Terrestrial Magnetism	$ 1,597,610	$1,202,865	$ 146,408	$ 2,946,883	$ 2,341,934
Mount Wilson and Las Campanas Observatories	3,022,361	619,167	100,924	3,742,452	3,662,817
Geophysical Laboratory	1,673,660	489,323	228,309	2,391,292	2,203,581
Embryology	937,222	1,650,456	396,574	2,984,252	2,516,778
Plant Biology	1,413,411	194,651	154,927	1,762,989	1,401,792
Research projects, etc.	54,585	...	15,000	69,585	80,145
Total	8,698,849	4,156,462	1,042,142	13,897,453	12,207,047
Administrative and general expenses					
Office of Administration	1,242,331	...	...	1,242,331	1,196,697
General publications	63,150	...	...	63,150	80,207
Professional fees, insurance, and taxes	208,262	...	...	208,262	326,647
Retiree and special employee benefits	202,132	...	...	202,132	203,456
Investment services	389,097	...	...	389,097	411,115
Total	2,104,972	...	...	2,104,972	2,218,122
Total expenses	$10,803,821	$4,156,462	$1,042,142	$16,002,425	$14,425,169

The accompanying notes are an integral part of these schedules.

CHANGES IN FUND BALANCES
FOR THE YEAR ENDED JUNE 30, 1985

	Balance July 1, 1984	Investment, Grant, and Other Income	Endowment and Special Gifts	Realized Net Capital Gains	Expenses	Other	Balance June 30, 1985
Endowment Funds							
Andrew Carnegie	$ 22,000,000	...	...	...	...	...	$ 22,000,000
Sybil & William T. Golden	25,000	...	...	...	...	...	25,000
Anonymous gifts	1,640,175	...	$ 250,000	...	...	...	1,890,175
Mellon Matching	1,186,547	...	261,909	...	...	...	1,448,456
Astronomy Matching	898,900	...	601,100	...	...	...	1,500,000
Realized capital gains	71,978,036	...	...	$6,077,179	...	...	78,055,215
Unrestricted Capital Funds							
Carnegie Corporation	10,000,000	...	...	...	...	...	10,000,000
Carnegie Futures	276,117	...	...	...	...	...	276,117
Vannevar Bush	100,000	...	...	...	...	...	100,000
Realized capital gains	15,211,691	...	...	1,700,302	...	...	16,911,993
Working Capital Fund	234,012	$10,978,451	...	...	$10,672,253	...	540,210
Restricted Grants	...	5,198,604	...	...	5,198,604	...	...
Special Funds							
Astronomy	1,136,437	112,726	...	94,058	...	$426,013	1,769,234
Ira S. and Mary Bowen	525,999	45,259	...	32,944	10,910	...	593,292
Bush Gift	76,986	7,985	...	5,852	...	...	90,823
Colburn	456,302	40,774	...	29,487	20,000	...	506,563
Hale Relief	18,219	1,730	...	1,268	...	...	21,217
Harkavy	21,016	1,760	...	1,263	1,000	...	23,039
Lundmark	81,718	6,628	...	4,858	...	...	93,204
Morganroth	64,889	4,802	...	3,520	...	...	73,211
Moseley Astronomy	194,459	15,522	...	11,227	9,316	...	211,892
Francis L. Moseley Gift	107,869	9,039	...	6,625	...	...	123,533
Roberts Memorial	68,580	6,025	850	4,438	...	...	79,893
Special Instrumentation	261,116	20,624	...	15,116	...	...	296,856
Special Opportunities	143,542	12,496	...	9,159	...	...	165,197
Wood	1,258,605	95,285	...	68,825	90,342	...	1,332,373
Plant Fund	15,291,087	...	...	...	...	316,793	15,607,880
Totals	$143,257,302	$16,557,710	$1,113,859	$8,066,121	$16,002,425	$742,806	$153,735,373
Adjustment to lower of cost or market	(542,276)						...
Fund balance	$142,715,026						$153,735,373

The accompanying notes are an integral part of these schedules.

SCHEDULE 3

RESTRICTED GRANTS
FOR THE YEAR ENDED JUNE 30, 1985

	Balance July 1, 1984	New Grants	Expenses	Balance June 30, 1985
Federal Grants				
BARD (U.S.–Israel Agriculture Fund)	$ 7,555	$ ...	$ 444	$ 7,111
National Aeronautics and Space Administration	384,076	286,324	463,174	207,226
National Science Foundation	1,006,325	1,616,751	1,437,400	1,185,676
Office of Naval Research	42,516	90,055	84,876	47,695
Public Health Service	999,845	1,569,546	1,657,010	912,381
U.S. Agency for International Development	400,525	...	312,300	88,225
U.S. Department of Agriculture	34,207	58,000	71,856	20,351
U.S. Department of Commerce	10,120	...	9,957	163
U.S. Department of Energy	27,025	6,000	28,548	4,477
U.S. Department of the Interior	122,637	...	90,897	31,740
Total federal grants	3,034,831	3,626,676	4,156,462	2,505,045
Private grants				
American Cancer Society	617,097	165,896	120,210	662,783
Anonymous	254,972	...	...	254,972
University of Basel	...	5,137	5,137	...
California Institute of Technology	25,284	29,530	41,390	13,424
University of California	3,411	30,744	34,155	...
Carnegie Corporation of New York	375,000	...	125,000	250,000
People's Republic of China	...	290,504	104,271	186,233
Charles E. Culpeper Foundation, Inc.	100,000	...	100,000	...
The Jane Coffin Childs Memorial Fund for Medical Research	62,364	1,083	34,600	28,847
The Charles A. Dana Foundation, Inc.	5,168	...	5,168	...
Exxon Education Foundation	50,000	...	50,000	...
William R. Hewlett Lead Trust	988,776	5,480	563	993,693
Pioneer Hi-Bred International	51,198	...	31,697	19,501
Johns Hopkins University	...	33,723	21,428	12,295
W. M. Keck Foundation	224,114	...	25,303	198,811
John D. & Catherine T. MacArthur Foundation	...	15,000	15,000	...
The Andrew W. Mellon Foundation	742,557	...	48,268	694,289
Monsanto Company	30,000	...	8,864	21,136
Francis L. Moseley	154,598	(151,101)	3,497	...
Muscular Dystrophy Association	27,750	18,000	37,250	8,500
National Geographic Society	35,778	...	28,023	7,755
University of Nevada	...	2,600	2,600	...
Jessie Smith Noyes Foundation, Inc.	1,896	...	1,896	...
The Pew Memorial Trust	75,000	...	75,000	...
Richard B. T. Roberts	1,306	...	...	1,306
Vera C. Rubin	3,500	...	153	3,347
Damon Runyon–Walter Winchell Cancer Fund	...	108,280	44,800	63,480
Alfred P. Sloan Foundation	25,000	...	4,543	20,457
The Teagle Foundation, Inc.	11,000	30,000	31,000	10,000
United Agriseeds	...	30,000	28,083	1,917
Wenner-Gren Foundation	...	6,000	636	5,364
Helen Hay Whitney Foundation	51,000	...	13,607	37,393
Total private grants	3,916,769	620,876	1,042,142	3,495,503
Total restricted grants	6,951,600	$4,247,552	$5,198,604	6,000,548
Less cash not yet received from grants	5,341,152			3,589,335
Deferred income	$1,610,448			$2,411,213

The accompanying notes are an integral part of these schedules.

SCHEDULE 4

SCHEDULE OF EXPENSES
FOR THE YEARS ENDED JUNE 30, 1985 AND 1984

	1985			1984
	Endowment and Special	Restricted Grants	Total Expenses	Total Expenses
Salaries, fringe benefits, and payroll taxes				
Salaries	$ 5,133,225	$1,365,621	$ 6,498,846	$ 6,356,338
Fringe benefits and payroll taxes	1,417,163	346,978	1,764,141	1,539,657
Total	6,550,388	1,712,599	8,262,987	7,895,995
Fellowship grants	541,942	447,110	989,052	797,671
Awards, grants, and honoraria	44,705	...	44,705	52,194
Equipment				
Educational and research	736,187	538,234	1,274,421	985,542
Administrative and operating	117,151	12,986	130,137	138,397
Library	107,333	2,379	109,712	102,284
Land (improvement)	...	...	...	16,995
Building (improvement)	359,108	563	359,671	18,232
Telescopes (improvement)	6,725	...	6,725	29,171
Total	1,326,504	554,162	1,880,666	1,290,621
General expenses				
Educational and research supplies	629,111	1,012,196	1,641,307	1,207,487
Building maintenance	878,859	...	878,859	1,006,463
Investment services	389,097	...	389,097	411,115
Administrative	653,903	4,618	658,521	578,801
Travel	256,417	238,068	494,485	354,238
Retiree and special employee benefits	202,132	...	202,132	195,222
General insurance	56,762	...	56,762	184,887
Publications	122,574	33,548	156,122	166,920
Professional and consulting fees	209,728	...	209,728	159,408
Commissary	49,954	...	49,954	56,812
Shop	37,086	...	37,086	33,026
Real estate and other taxes	29,751	...	29,751	8,930
Rent	6,211	15,000	21,211	25,379
Total	3,521,585	1,303,430	4,825,015	4,388,688
Indirect costs	(1,181,303)	1,181,303	...	...
Total expenses	$10,803,821	$5,198,604	$16,002,425	$14,425,169

The accompanying notes are an integral part of these schedules.

SCHEDULE 5
1 OF 4

SCHEDULE OF INVESTMENTS
JUNE 30, 1985

Description	Par/Shares	Cost	Approximate Market
Fixed income—short term			
General Motors Acceptance Corp., PN	710,000	$ 710,000	$ 710,000
Merck & Co., Inc., Master Note	2,054,000	2,054,000	2,054,000
Total fixed income—short term		2,764,000	2,764,000
Fixed income—bonds			
Chevron Capital USA Inc., Notes 11%, 1990	600,000	614,040	617,250
Equitable Life Leasing Corp Med Term Note, 11%, 1989	600,000	600,000	632,250
Equitable Life Leasing Corp Med Term Note, 11.85%	27,085	27,565	27,118
First Interstate Bancorp, Med Term Note 10.45%, 1998	650,000	650,507	658,938
Ford Motor Credit Co., Med Term Note, 10.25%	2,500,000	2,500,000	2,506,250
General Motors Acceptance Corp., Note, 9.75%, 1998	2,000,000	1,999,440	2,005,000
Hibernia National Bank, Ctf of Dep., 10.85%, 1986	600,000	600,000	608,250
Occidental Petroleum Corp., Note, Conv Sub Var Rate, 1988	1,200,000	1,213,000	1,201,500
Phillips Petroleum Co., SR Note FR, 11.25%, 1995	1,250	987	1,222
Phillips Petroleum Co., SR Note FR, 13.87%, 1997	360	284	378
Phillips Petroleum Co., Sub Deb, 14.75%, 2000	1,300	1,027	1,388
Republic Bank Dallas, Ctf of Dep, 10.55%, 1988	600,000	600,000	609,750
Sperry Lease Finance Corp., Leased Back Note, 11%, 1991	452,920	462,545	465,375
Wells Fargo & Co., Med Term Note, 10.6%, 1988	1,600,000	1,600,000	1,624,000
United States Treasury Bond, 7.62%, 2007	1,035,000	768,488	786,600
United States Treasury Bond, 10.37%, 2012	1,520,000	1,530,450	1,483,900
United States Treasury Note, 11.75%, 1993	3,850,000	3,934,594	4,158,000
United States Treasury Note, 14.50%, 1989	2,140,000	2,453,644	2,469,025
United States Treasury Note, 12.62%, 1994	6,325,000	7,071,531	7,170,969
Unocal Corp., Ext Note Adj Rate, 13.5%, 1988	900,000	942,188	941,625
Total fixed income—bonds		27,570,290	27,968,788
Fixed income—mortgages			
FHLMC, Group #180738, 7%, 2011	1,864,832	1,118,899	1,505,852
FHLMC, Group #181062, 6%, 2008	2,710,483	1,504,313	2,127,729
FHLMC, Group #185180, 8.75%, 2008	3,089,559	2,461,993	2,776,741
FNMA, Pool #280, 8.5%, 2012	3,988,028	2,671,978	3,494,509
FNMA, Pool #282, 8.5%, 2011	2,309,444	1,593,516	2,014,990
FNMA, Pool #1149, 8%, 2009	4,300,419	3,225,314	3,687,609
FNMA, Pool #2688, 7.75%, 2008	2,790,019	2,158,777	2,259,915
FNMA, Pool #2426, 7.75%, 2008	2,705,780	2,078,377	2,249,180
Home Savings of America, Series #198310, FHA & VA	1,123,123	930,789	1,020,638
Mortgage Corp. of the South, PC85-1, 9.64%, 2008	69,963	58,835	69,693
Security Savings & Loan Assn., Series #1984-3, Conventional Mtg Lns	3,009,498	2,431,886	2,554,311
GNMA, Pool #17519, 7.5%, 2007	492,228	382,093	399,935
Total fixed income—mortgages		20,616,770	24,161,102

The accompanying notes are an integral part of these schedules. *(continued)*

SCHEDULE 5
2 OF 4

SCHEDULE OF INVESTMENTS JUNE 30, 1985 (continued)

Description	Par/Shares	Cost	Approximate Market
Corporate stocks—common			
Abbott Laboratories	6,000	337,580	344,250
Advanced Micro Devices, Inc.	17,425	503,308	453,050
Aetna Life & Casualty	10,625	462,183	495,391
Alamito Co.	2	74	208
American Home Products Corp.	4,250	248,179	271,469
American International Group	1,700	128,172	144,500
American Information Technologies Co.	23,285	1,604,497	2,209,164
American President Co.	13,600	239,533	277,100
American Telephone & Telegraph Co.	171	2,855	4,125
AMR Corp.	12,750	549,790	610,406
Amstead Industries, Inc.	4,250	173,740	169,469
Aluminum Company of America	42,185	1,317,879	1,444,836
Amax, Inc.	8,500	148,164	126,438
Arizona Bancwest Corp.	23,100	364,875	701,663
Arvin Industries, Inc.	13,600	269,263	278,800
Avon Products, Inc.	10,795	223,394	230,743
Barnett Banks of Florida, Inc.	16,950	478,136	639,863
Bausch & Lomb, Inc.	24,225	663,894	787,313
Bell Atlantic Corp.	16,985	1,144,984	1,573,236
Black & Decker Mfg. Co.	5,100	94,388	100,725
Boeing Co.	56,961	2,142,662	2,549,005
Boise Cascade Corp.	12,250	508,816	591,063
Calmat	14,450	354,447	361,250
Caterpillar Tractor Co.	8,330	263,023	275,931
Cessna Aircraft Co.	5,780	108,712	131,495
Champion International Corp.	8,500	190,307	196,563
Chemed Corp.	12,500	323,043	373,438
Chesebrough-Pond's Inc.	4,590	158,965	146,880
Chrysler Corp.	11,550	420,672	421,575
Coco-Cola Co.	10,000	700,637	693,750
Commonwealth Edison	3,485	100,045	107,599
A. T. Cross Co.	4,165	129,213	143,693
Dana Corp.	17,700	390,754	484,538
Data General Corp.	3,400	129,897	127,075
Delta Air Lines	9,350	386,954	458,150
Deere & Co.	7,650	212,906	230,456
Detroit Edison Co.	3,910	63,811	66,959
Digital Equipment Corp.	14,750	1,502,093	1,384,656
Dow Chemical Co.	23,205	735,266	829,579
Dresser Industries Inc.	2,550	50,860	54,506
Duke Power	27,300	827,736	948,675
E. I. Du Pont de Nemours	3,655	202,097	212,447
Eastman Kodak Co.	7,649	337,157	338,468
Jack Eckerd Corp.	7,990	206,334	237,703
Economics Laboratory Inc.	4,420	126,942	146,965
Emerson Electric Co.	8,060	572,509	591,403
Farmers Group Inc.	14,500	501,875	933,438
Federal Express Corp.	20,400	767,382	905,250
First Alabama Bancshares Inc.	30,400	539,600	896,800
First Bank System Inc.	14,700	415,900	582,488
First Union Corp.	11,000	258,500	445,500
Ford Motor Corp.	5,950	244,267	268,494
General Electric Co.	17,000	1,040,510	1,051,875
General Motors Corp.	24,725	1,849,232	1,780,200
General Public Utilities Corp.	44,201	555,602	624,339

The accompanying notes are an integral part of these schedules. *(continued)*

SCHEDULE 5
3 OF 4

SCHEDULE OF INVESTMENTS JUNE 30, 1985 (continued)

Description	Par/Shares	Cost	Approximate Market
Corporate stocks—common (continued)			
Hewlett-Packard Co.	19,950	661,732	698,250
Hospital Corporation of America	8,000	357,838	388,000
Household International, Inc.	7,650	266,289	281,138
Imperial Chemical Industries	6,800	246,194	266,050
Intel Corp.	8,500	230,031	221,000
International Business Machines Corp.	49,700	5,644,889	6,150,364
International Paper Co.	7,380	370,172	361,620
IU International Corp.	5,100	112,520	67,575
Johnson & Johnson	25,500	1,140,989	1,182,563
Koppers Co., Inc.	25,500	448,861	452,625
Kroger Co.	2,890	123,056	131,134
Eli Lilly & Co.	12,750	998,953	1,102,875
Lubrizol Corp.	2,550	57,872	56,419
Lucky Stores Inc.	14,195	282,670	322,936
MCA Inc.	14,450	746,172	865,194
McDonalds Corp.	13,050	880,030	893,925
Mack Trucks Inc.	7,650	89,797	80,325
R. H. Macy & Co., Inc.	7,000	352,632	362,250
Maryland National Corp.	26,400	394,350	815,100
The Mead Corp.	19,975	786,159	843,944
Medtronic, Inc.	4,505	128,944	148,102
Merck & Co.	5,000	539,467	563,125
Milipore Corp.	291	10,021	11,422
Minnesota Mining & Mfg. Co.	3,570	273,004	278,460
Mobil Corp.	5,015	154,562	151,077
Monsanto Co.	14,750	690,049	713,531
Philip Morris Inc.	25,805	1,446,775	2,203,102
Motorola, Inc.	17,850	565,705	609,131
NCNB Corp.	38,500	919,122	1,674,750
NWA, Inc.	19,550	747,535	1,058,144
National Australia Bank Ltd.	178,000	520,640	511,750
New England Electric System	6,800	275,094	296,650
Nike Inc.	10,200	113,688	109,650
Northeast Utilities	6,120	95,992	102,510
Northwest Corp.	10,000	257,793	272,500
Nynex Corp.	16,500	1,020,411	1,472,625
Ohio Casualty Corp.	6,045	264,829	373,279
Orbanco Financial Services	18,200	533,075	313,950
Pacific Telesis Group	11,625	828,914	911,109
J.C. Penney Co., Inc.	4,080	190,516	210,120
Pennzoil Co.	2,465	126,220	125,715
Polaroid Corp.	25,500	718,995	803,250
Procter & Gamble Co.	4,845	252,885	272,531
Public Service Electric & Gas Co.	41,440	1,077,440	1,263,920
Raytheon Co.	6,375	286,493	318,750
R. J. Reynolds Industries Inc.	26,307	822,601	835,247
Rohm & Haas Co.	8,500	505,588	559,938
Royal Dutch Petroleum Co.	7,825	415,833	457,763
Safeway Stores, Inc.	5,865	174,161	198,677
Sante Fe–Southern Pacific	14,450	389,517	480,463
Schering-Plough Corp.	7,500	352,432	335,625
Schlumberger Limited	12,560	486,208	485,130
Sea-land Corp.	11,901	224,354	272,235
G. D. Searle & Co.	18,700	940,510	1,009,800
Shawmut Corp.	9,700	263,517	368,600

The accompanying notes are an integral part of these schedules. *(continued)*

SCHEDULE 5
4 OF 4

SCHEDULE OF INVESTMENTS JUNE 30, 1985 (continued)

Description	Par/Shares	Cost	Approximate Market
Corporate stocks—common (continued)			
Shell Transportation	12,300	375,950	453,563
SmithKline Beckman	12,950	800,268	901,644
Southeast Banking Corp.	26,900	539,158	921,325
Southern California Edison Co.	2,550	65,204	68,213
Southwestern Bell Corp.	26,570	1,656,232	2,231,880
Square D Co.	4,250	155,537	168,406
Squibb Corp.	5,100	286,008	321,938
Tandem Computers Inc.	22,950	458,268	415,969
Tektronix, Inc.	12,750	734,268	771,375
Temple Inland Inc.	8,500	291,805	286,875
Tenneco Inc.	20,760	826,773	879,705
Texaco Inc.	18,400	720,139	696,900
Texas Instruments Inc.	595	78,669	56,897
Texas Oil & Gas Corp.	5,440	96,941	89,080
Texas Utilities Co.	4,845	135,216	150,195
Tucson Electric Power Co.	28	955	1,145
Timken Co.	5,016	251,599	237,633
UAL Inc.	18,700	782,609	1,002,788
Upjohn Co.	13,175	1,178,932	1,426,194
USF&G Corp.	6,290	208,526	231,158
USWest Corp.	17,680	1,049,528	1,432,080
United States Steel Corp.	7,565	207,669	210,874
United Technologies Corp.	26,445	918,748	1,097,468
Xerox Corp.	6,375	291,887	335,484
Washington Gas Light Co.	28,200	540,775	648,600
Wells Fargo & Co.	2,380	128,285	141,610
Westinghouse Electric Corp.	40,550	944,212	1,393,906
Westpac Banking Ltd.	178,000	505,920	489,500
Subtotal corporate stocks—common		71,307,791	82,833,278
Corporate stocks—preferred			
United Technologies Corp.	5,600	196,630	205,100
Subtotal corporate stock—preferred		196,630	205,100
Corporate stocks—mutual fund			
Miller, Anderson & Sherrerd Value Fund	501,000	12,672,328	14,729,400
Subtotal corporate stocks—mutual fund		12,672,328	14,729,400
Total corporate stocks		84,176,749	97,767,778
Other			
Alan Dressler, Second trust, variable interest rate		59,244	59,244
James D. and Alma C. Ebert (non-interest-bearing loan to president secured by real estate)		200,000	200,000
Arthur Grossman, First trust, 9.0%, 2014		93,131	93,131
Steven McKnight, First trust, 10.5%, 2009		99,280	99,280
François Schweizer, First trust, 10.5%, 2007		96,904	96,904
Total other		548,559	548,559
Total investments		$ 135,676,368	$ 153,210,227

The accompanying notes are an integral part of these schedules.

Articles of Incorporation

Fifty-eighth Congress of the United States of America;

At the Second Session,

Begun and held at the City of Washington on Monday, the seventh day of December, one thousand nine hundred and three.

AN ACT

To incorporate the Carnegie Institution of Washington.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, That the persons following, being persons who are now trustees of the Carnegie Institution, namely, Alexander Agassiz, John S. Billings, John L. Cadwalader, Cleveland H. Dodge, William N. Frew, Lyman J. Gage, Daniel C. Gilman, John Hay, Henry L. Higginson, William Wirt Howe, Charles L. Hutchinson, Samuel P. Langley, William Lindsay, Seth Low, Wayne MacVeagh, Darius O. Mills, S. Weir Mitchell, William W. Morrow, Ethan A. Hitchcock, Elihu Root, John C. Spooner, Andrew D. White, Charles D. Walcott, Carroll D. Wright, their associates and successors, duly chosen, are hereby incorporated and declared to be a body corporate by the name of the Carnegie Institution of Washington and by that name shall be known and have perpetual succession, with the powers, limitations, and restrictions herein contained.

SEC. 2. That the objects of the corporation shall be to encourage, in the broadest and most liberal manner, investigation, research, and discovery, and the application of knowledge to the improvement of mankind; and in particular—

(a) To conduct, endow, and assist investigation in any department of science, literature, or art, and to this end to cooperate with governments, universities, colleges, technical schools, learned societies, and individuals.

(b) To appoint committees of experts to direct special lines of research.

(c) To publish and distribute documents.

(d) To conduct lectures, hold meetings, and acquire and maintain a library.

(e) To purchase such property, real or personal, and construct such building or buildings as may be necessary to carry on the work of the corporation.

(f) In general, to do and perform all things necessary to promote the objects of the institution, with full power, however, to the trustees hereinafter appointed and their successors from time to time to modify the conditions and regulations under which the work shall be carried on, so as to secure the application of the funds in the manner best adapted to the conditions of the time, provided that the objects of the corporation shall at all times be among the foregoing or kindred thereto.

SEC. 3. That the direction and management of the affairs of the corporation and the control and disposal of its property and funds shall be vested in a board of trustees, twenty-two in number, to be composed of the following individuals: Alexander Agassiz, John S. Billings, John L. Cadwalader, Cleveland H. Dodge, William N. Frew, Lyman J. Gage, Daniel C. Gilman, John Hay, Henry L. Higginson, William Wirt Howe, Charles L. Hutchinson, Samuel P. Langley, William Lindsay, Seth Low, Wayne MacVeagh, Darius O. Mills, S. Weir Mitchell, William W. Morrow, Ethan A. Hitchcock, Elihu Root, John C. Spooner, Andrew D. White, Charles D. Walcott, Carroll D. Wright, who shall constitute the first board of trustees. The board of trustees shall have power from time to time to increase its membership to not more than twenty-seven members. Vacancies occasioned by death, resignation, or otherwise shall be filled by the remaining trustees in such manner as the by-laws shall prescribe; and the persons so elected shall thereupon become trustees and also members of the said corporation. The principal place of business of the said corporation shall be the city of Washington, in the District of Columbia.

SEC. 4. That such board of trustees shall be entitled to take, hold and administer the securities, funds, and property so transferred by said Andrew Carnegie to the trustees of the Carnegie Institution and such other funds or property as may at any time be given, devised, or bequeathed to them, or to such corporation, for the purposes of the trust; and with full power from time to time to adopt a common seal, to appoint such officers, members of the board of trustees or otherwise, and such employees as may be deemed necessary in carrying on the business of the corporation, at such salaries or with such remuneration as they may deem proper; and with full power to adopt by-laws from time to time and such rules or regulations as may be necessary to secure the safe and convenient transaction of the business of the corporation; and with full power and discretion to deal with and expend the income of the corporation in such manner as in their judgment will best promote the objects herein set forth and in general to have and use all powers and authority necessary to promote such objects and carry out the purposes of the donor. The said trustees shall have further power from time

to time to hold as investments the securities hereinabove referred to so transferred by Andrew Carnegie, and any property which has been or may be transferred to them or such corporation by Andrew Carnegie or by any other person, persons, or corporation, and to invest any sums or amounts from time to time in such securities and in such form and manner as are permitted to trustees or to charitable or literary corporations for investment, according to the laws of the States of New York, Pennsylvania, or Massachusetts, or in such securities as are authorized for investment by the said deed of trust so executed by Andrew Carnegie, or by any deed of gift or last will and testament to be hereafter made or executed.

SEC. 5. That the said corporation may take and hold any additional donations, grants, devises, or bequests which may be made in further support of the purposes of the said corporation, and may include in the expenses thereof the personal expenses which the trustees may incur in attending meetings or otherwise in carrying out the business of the trust, but the services of the trustees as such shall be gratuitous.

SEC. 6. That as soon as may be possible after the passage of this Act a meeting of the trustees hereinbefore named shall be called by Daniel C. Gilman, John S. Billings, Charles D. Walcott, S. Weir Mitchell, John Hay, Elihu Root, and Carroll D. Wright, or any four of them, at the city of Washington, in the District of Columbia, by notice served in person or by mail addressed to each trustee at his place of residence; and the said trustees, or a majority thereof, being assembled, shall organize and proceed to adopt by-laws, to elect officers and appoint committees, and generally to organize the said corporation; and said trustees herein named, on behalf of the corporation hereby incorporated, shall thereupon receive, take over, and enter into possession, custody, and management of all property, real or personal, of the corporation heretofore known as the Carnegie Institution, incorporated, as hereinbefore set forth under "An Act to establish a Code of Law for the District of Columbia, January fourth, nineteen hundred and two," and to all its rights, contracts, claims, and property of any kind or nature; and the several officers of such corporation, or any other person having charge of any of the securities, funds, real or personal, books or property thereof, shall, on demand, deliver the same to the said trustees appointed by this Act or to the persons appointed by them to receive the same; and the trustees of the existing corporation and the trustees herein named shall and may take such other steps as shall be necessary to carry out the purposes of this Act.

SEC. 7. That the rights of the creditors of the said existing corporation known as the Carnegie Institution shall not in any manner be impaired by the

passage of this Act, or the transfer of the property hereinbefore mentioned, nor shall any liability or obligation for the payment of any sums due or to become due, or any claim or demand, in any manner or for any cause existing against the said existing corporation, be released or impaired; but such corporation hereby incorporated is declared to succeed to the obligations and liabilities and to be held liable to pay and discharge all of the debts, liabilities, and contracts of the said corporation so existing to the same effect as if such new corporation had itself incurred the obligation or liability to pay such debt or damages, and no such action or proceeding before any court or tribunal shall be deemed to have abated or been discontinued by reason of the passage of this Act.

SEC. 8. That Congress may from time to time alter, repeal, or modify this Act of incorporation, but no contract or individual right made or acquired shall thereby be divested or impaired.

SEC. 9. That this Act shall take effect immediately.

J. G. Cannon

Speaker of the House of Representatives.

Jno. C. Spooner

President of the Senate pro tempore.

Approved.
April 28, 1904.
Theodore Roosevelt

By-Laws of the Institution

Adopted December 13, 1904. Amended December 13, 1910, December 13, 1912, December 10, 1937, December 15, 1939, December 13, 1940, December 18, 1942, December 12, 1947, December 10, 1954, October 24, 1957, May 8, 1959, May 13, 1960, May 10, 1963, May 15, 1964, March 6, 1967, May 3, 1968, May 14, 1971, August 31, 1972, May 9, 1974, April 30, 1976, May 1, 1981, May 7, 1982, and May 3, 1985.

ARTICLE I

The Trustees

1.1. The Board of Trustees shall consist of twenty-four members with power to increase its membership to not more than twenty-seven members.

1.2. The Board of Trustees shall be divided into three classes each having eight or nine members. The terms of the Trustees shall be such that those of the members of one class expire at the conclusion of each annual meeting of the Board. At each annual meeting of the Board vacancies resulting from the expiration of Trustees' terms shall be filled by their re-election or election of their successors. Trustees so re-elected or elected shall serve for terms of three years expiring at the conclusion of the annual meeting of the Board in the third year after their election. A vacancy resulting from the resignation, death, or incapacity of a Trustee before the expiration of his* term may be filled by election of a successor at or between annual meetings. A person elected to succeed a Trustee before the expiration of his term shall serve for the remainder of that term. There shall be no limit on the number of terms for which a Trustee may serve, and a Trustee shall be eligible for immediate re-election upon expiration of his term.

1.3. No Trustee shall receive any compensation for his services as such.

1.4. Trustees shall be elected by vote of two-thirds of the Trustees present at a meeting of the Board of Trustees at which a quorum is present or without a meeting by written action of all of the Trustees pursuant to Section 4.6.

1.5. If, at any time during an emergency period, there be no surviving Trustee capable of acting, the President, the Director of each existing Department, or such of them as shall then be surviving and capable of acting, shall constitute a Board of Trustees *pro tem*, with full powers under the provisions of the Articles of Incorporation and these By-Laws. Should neither the President nor any such Director be capable of acting, the senior surviving Staff Member of each existing Department shall be a Trustee *pro tem* with full powers of a Trustee under the Articles of Incorporation and these By-Laws. It shall be incumbent on the Trustees *pro tem* to reconstitute the Board with permanent members within a reasonable time after the emergency has passed, at which time the Trustees *pro tem* shall cease to hold office. A list of Staff Member seniority, as designated annually by the President, shall be kept in the Institution's records.

1.6. A Trustee who resigns after having served at least six years and having reached age seventy shall be eligible for designation by the Board of Trustees as a Trustee Emeritus. A Trustee Emeritus shall be entitled to attend meetings of the Board but shall have no vote and shall not be counted for purposes of ascertaining the presence of a quorum. A Trustee Emeritus may be invited to serve in an advisory capacity on any committee of the Board except the Executive Committee.

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*A masculine pronoun as used in these By-Laws shall be deemed to include the corresponding female pronoun.

ARTICLE II

Officers of the Board

2.1. The officers of the Board shall be a Chairman of the Board, a Vice-Chairman, and a Secretary, who shall be elected by the Trustees, from the members of the Board, by ballot to serve for a term of three years. All vacancies shall be filled by the Board for the unexpired term; provided, however, that the Executive Committee shall have power to fill a vacancy in the office of Secretary to serve until the next meeting of the Board of Trustees.

2.2. The Chairman shall preside at all meetings and shall have the usual powers of a presiding officer.

2.3. The Vice-Chairman, in the absence or disability of the Chairman, shall perform the duties of the Chairman.

2.4. The Secretary shall issue notices of meetings of the Board, record its transactions, and conduct that part of the correspondence relating to the Board and to his duties.

ARTICLE III

Executive Administration

3.1. There shall be a President who shall be elected by ballot by, and hold office during the pleasure of, the Board, who shall be the chief executive officer of the Institution. The President, subject to the control of the Board and the Executive Committee, shall have general charge of all matters of administration and supervision of all arrangements for research and other work undertaken by the Institution or with its funds. He shall prepare and submit to the Board of Trustees and to the Executive Committee plans and suggestions for the work of the Institution, shall conduct its general correspondence and the correspondence with applicants for grants and with the special advisors of the Committee, and shall present his recommendations in each case to the Executive Committee for decision. All proposals and requests for grants shall be referred to the President for consideration and report. He shall have power to remove, appoint, and, within the scope of funds made available by the Trustees, provide for compensation of subordinate employees and to fix the compensation of such employees within the limits of a maximum rate of compensation to be established from time to time by the Executive Committee. He shall be *ex officio* a member of the Executive Committee.

3.2. The President shall be the legal custodian of the seal and of all property of the Institution whose custody is not otherwise provided for. He shall sign and execute on behalf of the corporation all contracts and instruments necessary in authorized administrative and research matters and affix the corporate seal thereto when necessary, and may delegate the performance of such acts and other administrative duties in his absence to other officers. He may execute all other contracts, deeds, and instruments on behalf of the corporation and affix the seal thereto when expressly authorized by the Board of Trustees or Executive Committee. He may, within the limits of his own authorization, delegate to other officers authority to act as custodian of and affix the corporate seal. He shall be responsible for the expenditure and disbursement of all funds of the Institution in accordance with the directions of the Board and of the Executive Committee, and shall keep accurate accounts of all receipts and disbursements. He shall, with the assistance of the Directors of the Departments, prepare for presentation to the Trustees and for publication an annual report on the activities of the Institution.

3.3. The President shall attend all meetings of the Board of Trustees.

3.4. The corporation shall have such other officers as may be appointed by the Executive Committee, having such duties and powers as may be specified by the Executive Committee or by the President under authority from the Executive Committee.

3.5. The President shall retire from office at the end of the fiscal year in which he becomes sixty-five years of age.

ARTICLE IV

Meetings and Voting

4.1. The annual meeting of the Board of Trustees shall be held in the City of Washington, in the District of Columbia, in May of each year on a date fixed by the Executive Committee, or at such other time or such other place as may be designated by the Executive Committee, or if not so designated prior to May 1 of such year, by the Chairman of the Board of Trustees, or if he is absent or is unable or refuses to act, by any Trustee with the written consent of the majority of the Trustees then holding office.

4.2. Special meetings of the Board of Trustees may be called, and the time and place of meeting designated, by the Chairman, or by the Executive Committee, or by any Trustee with the written consent of the majority of the Trustees then holding office. Upon the written request of seven members of the Board, the Chairman shall call a special meeting.

4.3. Notices of meetings shall be given ten days prior to the date thereof. Notice may be given to any Trustee personally, or by mail or by telegram sent to the usual address of such Trustee. Notices of adjourned meetings need not be given except when the adjournment is for ten days or more.

4.4. The presence of a majority of the Trustees holding office shall constitute a quorum for the transaction of business at any meeting. An act of the majority of the Trustees present at a meeting at which a quorum is present shall be the act of the Board except as otherwise provided in these By-Laws. If, at a duly called meeting, less than a quorum is present, a majority of those present may adjourn the meeting from time to time until a quorum is present. Trustees present at a duly called or held meeting at which a quorum is present may continue to do business until adjournment notwithstanding the withdrawal of enough Trustees to leave less than a quorum.

4.5. The transactions of any meeting, however called and noticed, shall be as valid as though carried out at a meeting duly held after regular call and notice, if a quorum is present and if, either before or after the meeting, each of the Trustees not present in person signs a written waiver of notice, or consent to the holding of such meeting, or approval of the minutes thereof. All such waivers, consents, or approvals shall be filed with the corporate records or made a part of the minutes of the meeting.

4.6. Any action which, under law or these By-Laws, is authorized to be taken at a meeting of the Board of Trustees or any of the Standing Committees may be taken without a meeting if authorized in a document or documents in writing signed by all the Trustees, or all the members of the Committee, as the case may be, then holding office and filed with the Secretary.

4.7. During an emergency period the term "Trustees holding office" shall, for purposes of this Article, mean the surviving members of the Board who have not been rendered incapable of acting for any reason including difficulty of transportation to a place of meeting or of communication with other surviving members of the Board.

ARTICLE V

Committees

5.1. There shall be the following Standing Committees, *viz.* an Executive Committee, a Finance Committee, an Auditing Committee, a Nominating Committee, and an Employee Benefits Committee.

5.2. All vacancies in the Standing Committees shall be filled by the Board of Trustees at the next annual meeting of the Board and may be filled at a special meeting of the

Board. A vacancy in the Executive Committee and, upon request of the remaining members of any other Standing Committee, a vacancy in such other Committee may be filled by the Executive Committee by temporary appointment to serve until the next meeting of the Board.

5.3. The terms of all officers and of all members of Committees, as provided for herein, shall continue until their successors are elected or appointed. The term of any member of a Committee shall terminate upon termination of his service as a Trustee.

Executive Committee

5.4. The Executive Committee shall consist of the Chairman, Vice-Chairman, and Secretary of the Board of Trustees, the President of the Institution *ex officio,* and, in addition, not less than five or more than eight Trustees to be elected by the Board by ballot for a term of three years, who shall be eligible for re-election. Any member elected to fill a vacancy shall serve for the remainder of his predecessor's term. The presence of four members of the Committee shall constitute a quorum for the transaction of business at any meeting.

5.5. The Executive Committee shall, when the Board is not in session and has not given specific directions, have general control of the administration of the affairs of the corporation and general supervision of all arrangements for administration, research, and other matters undertaken or promoted by the Institution. It shall also submit to the Board of Trustees a printed or typewritten report of each of its meetings, and at the annual meeting shall submit to the Board a report for publication.

5.6. The Executive Committee shall have power to authorize the purchase, sale, exchange, or transfer of real estate.

Finance Committee

5.7. The Finance Committee shall consist of not less than five and not more than six members to be elected by the Board of Trustees by ballot for a term of three years, who shall be eligible for re-election. The presence of three members of the Committee shall constitute a quorum for the transaction of business at any meeting.

5.8. The Finance Committee shall have custody of the securities of the Institution and general charge of its investments and invested funds and shall care for and dispose of the same subject to the directions of the Board of Trustees. It shall have power to authorize the purchase, sale, exchange, or transfer of securities and to delegate this power. So long as the Institution is the trustee under any retirement or other benefit plan for the staff members and employees of the Institution, it shall be responsible for supervision of matters relating to investments thereunder and for the appointment or removal of any investment manager or advisor. It shall also be responsible for reviewing the financial status and arrangements of any employee benefit plan for which the Institution is not the trustee and for appointment or removal of any plan trustee or insurance carrier. It shall consider and recommend to the Board from time to time such measures as in its opinion will promote the financial interests of the Institution and improve the management of investments under any retirement or other benefit plan. The Committee shall make a report at the annual meeting of the Board.

Auditing Committee

5.9. The Auditing Committee shall consist of three members to be elected by the Board of Trustees by ballot for a term of three years.

5.10. Before each annual meeting of the Board of Trustees, the Auditing Committee shall cause the accounts of the Institution for the preceding fiscal year to be audited by public accountants. The accountants shall report to the Committee, and the Committee

shall present said report at the ensuing annual meeting of the Board with such recommendations as the Committee may deem appropriate.

Nominating Committee

5.11. The Nominating Committee shall consist of the Chairman of the Board of Trustees *ex officio* and, in addition, three Trustees to be elected by the Board by ballot for a term of three years, who shall not be eligible for re-election until after the lapse of one year. Any member elected to fill a vacancy shall serve for the remainder of his predecessor's term, provided that of the Nominating Committee first elected after adoption of this By-Law one member shall serve for one year, one member shall serve for two years, and one member shall serve for three years, the Committee to determine the respective terms by lot.

5.12. Sixty days prior to an annual meeting of the Board the Nominating Committee shall notify the Trustees by mail of the vacancies to be filled in membership of the Board. Each Trustee may submit nominations for such vacancies. Nominations so submitted shall be considered by the Nominating Committee, and ten days prior to the annual meeting the Nominating Committee shall submit to members of the Board by mail a list of the persons so nominated, with its recommendations for filling existing vacancies on the Board and its Standing Committees. No other nominations shall be received by the Board at the annual meeting except with the unanimous consent of the Trustees present.

Employee Benefits Committee

5.13. The Employee Benefits Committee shall consist of not less than three and not more than four members to be elected by the Board of Trustees by ballot for a term of three years, who shall be eligible for re-election, and the Chairman of the Finance Committee *ex officio.* Any member elected to fill a vacancy shall serve for the remainder of his predecessor's term.

5.14. The Employee Benefits Committee shall, subject to the directions of the Board of Trustees, be responsible for supervision of the activities of the administrator or administrators of any retirement or other benefit plan for staff members and employees of the Institution, except that any matter relating to investments or to the appointment or removal of any trustee or insurance carrier under any such plan shall be the responsibility of the Finance Committee. It shall receive reports from the administrator or administrators of the employee benefit plans with respect to administration, benefit structure, operation, and funding. It shall consider and recommend to the Board from time to time such measures as in its opinion will improve such plans and the administration thereof. The Committee shall submit a report to the Board at the annual meeting of the Board.

ARTICLE VI

Financial Administration

6.1. No expenditure shall be authorized or made except in pursuance of a previous appropriation by the Board of Trustees, or as provided in Section 5.8 of these By-Laws.

6.2. The fiscal year of the Institution shall commence on the first day of July in each year.

6.3. The Executive Committee shall submit to the annual meeting of the Board a full statement of the finances and work of the Institution for the preceding fiscal year and a detailed estimate of the expenditures of the succeeding fiscal year.

6.4. The Board of Trustees, at the annual meeting in each year, shall make general appropriations for the ensuing fiscal year; but nothing contained herein shall prevent the Board of Trustees from making special appropriations at any meeting.

6.5. The Executive Committee shall have general charge and control of all appropriations made by the Board. Following the annual meeting, the Executive Committee may allocate these appropriations for the succeeding fiscal year. The Committee shall have full authority to reallocate available funds, as needed, and to transfer balances.

6.6. The securities of the Institution and evidences of property, and funds invested and to be invested, shall be deposited in such safe depository or in the custody of such trust company and under such safeguards as the Finance Committee shall designate, subject to directions of the Board of Trustees. Income of the Institution available for expenditure shall be deposited in such banks or depositories as may from time to time be designated by the Executive Committee.

6.7. Any trust company entrusted with the custody of securities by the Finance Committee may, by resolution of the Board of Trustees, be made Fiscal Agent of the Institution, upon an agreed compensation, for the transaction of the business coming within the authority of the Finance Committee.

6.8. The property of the Institution is irrevocably dedicated to charitable purposes, and in the event of dissolution its property shall be used for and distributed to those charitable purposes as are specified by the Congress of the United States in the Articles of Incorporation, Public Law No. 260, approved April 28, 1904, as the same may be amended from time to time.

ARTICLE VII

Amendment of By-Laws

7.1. These By-Laws may be amended at any annual or special meeting of the Board of Trustees by a two-thirds vote of the members present, provided written notice of the proposed amendment shall have been served personally upon, or mailed to the usual address of, each member of the Board twenty days prior to the meeting.

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